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Reference Hydrologic Networks I. The Status Potential Future Directions of National Reference Hydrologic Networks for Detecting Trends

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Abstract Identifying climate-driven trends in river flows on a global basis is hampered by a lack of long, quality time series data for rivers with relatively undisturbed regimes. This is a global problem compounded by the lack of support for essential long-term monitoring. Experience demonstrates that with clear strategic objectives, and the support of sponsoring organizations, Reference Hydrologic Networks can constitute an exceptionally valuable data source to effectively identify, quantify and interpret hydrological change - the speed and magnitude of which is expected to a be a primary driver of water management and flood alleviation strategies through the future - and for additional applications. Reference hydrologic networks have been developed in many countries in the past few decades. These collections of streamflow gauging stations that are maintained and operated with the intention of observing how the hydrology of watersheds responds to variations in climate are described. The status of networks under development is summarized.. We suggest a plan of actions to make more effective use of this collection of networks.

Résumé

L’identification de tendances induites par le climat dans les débits de rivières est entravée par le manque de longues séries chronologiques de qualité provenant de rivières dont le régime est peu altéré. Ce problème global est aggravé par le manque de soutien aux initiatives de suivi à long terme. L’expérience démontre qu’avec des objectifs stratégiques clairs ainsi que le soutien des organismes de parrainage, les réseaux de référence hydrométriques peuvent s’avérer une précieuse source de données pour l’identification, la quantification et l’interprétation des changements hydrologiques. La vitesse et l’ampleur de ces derniers seront probablement des moteurs majeurs de la gestion de l’eau et de la lutte contre les inondations dans le futur. Pour cette raison, ainsi que pour d’autres applications, des réseaux de référence hydrologiques ont été développés dans plusieurs pays dans les quelques dernières décennies. Ces collections de stations de suivi hydrométrique, qui sont maintenues et exploitées dans l’intention d’observer la façon dont l’hydrologie des bassins versants répond aux variations climatiques, sont décrites et l’état actuel de développement des réseaux est résumé. Nous suggérons un plan d’action visant une utilisation plus efficace de ces réseaux.

Keywords: reference networks, hydrometric data, hydrologic change

Introduction

Over the past 15 years many countries have invested in reference hydrologic networks (RHN), collections of streamflow gauging stations that are maintained and operated with the intention of observing how the hydrology of watersheds responds to variations in climate (Stahl *et al.* 2010, Monk *et al*. 2011). For climate-sensitive hydrological observations, and discharge information in particular, a RHN needs to be defined with stable conditions and/or a minimum of direct human influences on the hydrological regime in the concerned basin. Data requirements for climate change detection studies are demanding; they should be based on good quality data from observation networks of rivers with near-natural conditions (Slack and Landwehr 1992, Harvey and Grabs 2003, Hannah *et al.* 2011).

In general, streamflow records from RHNs represent near-natural river flow regimes from catchments with varying hydrological characteristics, usually assumed to be representative of broad regions. These networks provide time series records for investigating the predominant climate and catchment processes that govern changes in regional hydrology. A further advantage of such networks is that the gauged catchments are typically small, by virtue of the need to minimise the impact of human disturbance. In larger catchments, processes with opposing hydrological influences may act simultaneously. For example, as a response to a warming trend in early summer, snowmelt in a catchment's mountain headwaters may increase but higher evapotranspiration in lowland regions may counter this effect, hence resulting in no net change at the downstream gauging station. Data from such "reference" networks are therefore of fundamental importance for detection and attribution studies and for validation of large-scale climate and hydrological models. The objective of the current article was to review and synthesize the development of RHNs from around the world based upon our collective national experiences; to assess the state of development and compare between networks; and to consider how to provide guidance for the future of these networks.

Hydrologic networks are designed to gather information on the quantity (and sometimes quality) of water moving through catchments and along rivers. The most common type of network is a set of water-level recorders: their records, together with periodic measurements of river flows, provide time series of river flows for each catchment monitored (Pearson 1998). Thus RHN's are subsets of such networks where the selection is based upon the following, or similar criteria (Slack and Landwehr 1992, Brimley *et al*. 1999, Harvey *et al.* 1999, Pilon and Yuzyk 2000, Hannaford and Marsh 2008). The criteria listed below are those listed in these published sources and the reader should be aware that these criteria are quite subjective and subject to interpretation.

1. **Degree of basin development.** Ideally, catchments that are pristine or have stable land-use conditions (<10% of the area is affected);
2. **Absence of significant regulations, diversions, or water use**. A catchment is considered natural only if there is no substantial control structure upstream or water extractions within the basin, or diversions between basins. When regulation is

present in a basin some gauging stations may be appropriate for analyzing high flows and average flows, but not for low flows;

3. **Record length**. Any RHN station must have a minimum record length of 20 years. This length ensures that underrepresented climatic or geographic areas, which are characterized by minimal data availability, are also included. However, record lengths should also be as long as possible to allow decadal variability to be distinguished from long-term trends;
4. **Active data collection.** A station is included in the network if it is currently active and is expected to continue operation until it achieves the desired record length;
5. **Data accuracy**. Only stations with what is considered good quality data are included in the network; and,
6. **Adequate metadata.** Adequate metadata should be available to support the previous five conditions.

These criteria are clearly aspirational and in capitalising effectively on existing hydrologic networks compromises are often required to ensure an enduring and geographically representative capability to capture and interpret climate-related hydrological trends. We expect that the original authors chose terms that were subjective and open to interpretation for this purpose.

Reference hydrologic networks are not a new concept. Nearly 60 years ago, Langbein and Hoyt (1959) and Leopold (1962) proposed the establishment of a hydrologic bench-mark network (HBN) in the United States to document natural changes in hydrologic characteristics with time, and to provide a comparative base for studying the effect of human activities on the hydrologic environment. The USGS HBN was established in 1968 and was comprised of 57 catchments (Cobb and Biesecker, 1971).

In 2006 the World Meteorological Organization (WMO) requested its members to identify “Stream gauging stations appropriate for climate studies”. The criteria for the identification of these stations are identical to the criteria for RHN as discussed, with the addition that the data should also be available in digital format. The Global Runoff Data Center (GRDC) is collating the provided information for the WMO with the intention to collect the discharge time series for the identified stations and include them in the GRDC data holdings, so that the data can be made available to research and science. Since 2008 GRDC requests for data and updates also include the identification of “Stream gauging stations appropriate for climate studies”. Table 1 provides a summary of the information and data available through the WMO request plus additional RHN not directly reported to the WMO or GRDC. Until now 28 countries have supplied station lists at various levels of completion and seven countries have provided the associated discharge data. From the responses to the WMO request it cannot be established whether the identified stations form part of a RHN or only meet (some of) the WMO stipulated criteria. In some countries, pristine watersheds are not available, and other criteria need to be used to select those that are sufficiently natural as to warrant inclusion in a RHN.

Table 1 near here

The definition of what constitutes a near-natural condition is likely to vary between networks. In the United States and particularly in Canada, for example, there are many catchments which can justifiably be called “pristine”. In the heavily populated parts of Europe, with long history of human disturbance, there are few pristine catchments, so some degree of disturbance must be tolerated. In the United Kingdom, for example, catchments where the net impact of abstractions and discharges are considered to be within 10% of the natural flow at, or in excess of the Q_{95} are deemed suitable for representative basin status (Marsh and Hannaford 2008). In many areas catchments have a high amount of agricultural land use. It may be appropriate to use these catchments in RHNs if agricultural practices have remained constant during the period of interest.

The criteria regarding the absence of regulation and diversions may also be problematic as the possibility exists that the magnitude of any effect from them might be negligible in a very large watershed, but because most RHN stations (nearly 70% are in basins less that 500 km^2) are in relatively small watersheds, regulation and diversions are more likely to have hydrological effects. Others argue that even large reservoirs have no effect on annual fluxes; rather their effect is only on monthly flows (Vörösmarty and Sahagian 2000, Vörösmarty *et al.* 2000) and hence the natural hydrologic variation is often overlooked. Because most large reservoirs are designed to not only shift water between seasons, but also between years, this should preclude basins with such large storages; but perhaps not those with diversions where little storage is present.

Similarly, the desired record length is not just for a nominal 20 years; rather, record lengths are required that span periods that cover the various states of climate indices in addition to the period over which changing climate is of interest. The sensitivity of hydrological trend detection to the time span of the records under review (Wilby *et al.* 2008) is such that, where possible, representative basin networks should include some time series of at least 50 years in length. Shorter records can be misleading because of multi-decadal streamflow oscillations. In rivers studied by Hamed (2008) and Khaliq *et al.* (2009), statistically significant positive and negative 40-year trends both existed for the same rivers within their full period of record.

Including stations in a reference network for climate studies which might someday have sufficient data may be anticipatory and users might misinterpret the suitability of such records. However, not including them in some fashion can be viewed by sponsors as a sign these stations are not worthy of continuing their operation. Finally, while no one would suggest that any such network should include ‘bad data’, flexibility needs to be exercised when assessing the value of available historical data which, though not of the quality which characterizes modern hydrometric practice, may still be of very high utility (e.g. providing important insights into longer term runoff variability).

It has been reported that the least impressive observational evidence in the most recent IPCC (Solomon *et al.* 2007) assessment was in the area of hydrologic change. There is no single global pattern of hydrological change in relation to climate change; the observed trends collectively can become confusing as streamflow increases or decreases because of changes in components of the hydrological cycle. In addition, not all the hydrological changes that have been observed in the past decades can be solely attributed to climate variations. Trenberth *et al.* (2007) report that large changes and trends in seasonal streamflow rates for many of the world’s major rivers should be interpreted with caution, because many of these streams have been affected by the construction of large dams and reservoirs that increase low flows and reduce peak flows. Land use change can also have significant effects on streamflow (e.g. Bronstert *et al.* 2002, Brandes *et al.* 2005, Schilling *et al.* 2010). Nevertheless, there is evidence that the rapid warming between the 1970s and 2000s had induced earlier snowmelt and associated peak streamflow in western North America (Dettinger and Cayan 1995, Leith and Whitfield 1998, Whitfield and Cannon 2000, Cayan *et al.* 2001, Regonda *et al.* 2005, Stewart *et al.* 2005) and eastern North America (Hodgkins *et al.* 2003, Hodgkins and Dudley 2006, Burns et. al. 2007) as well as earlier breakup of river ice in Russian Arctic rivers (Smith 2000), many Canadian rivers (Zhang *et al.* 2001), and rivers in the far northeastern United States (Hodgkins *et al.* 2005). To continue observing those changes, hydrologic networks are essential; in a companion paper, Burn *et al.* (2011) report on the use of RHN's for trend studies.

In several jurisdictions, RHNs have been established as a subset of the existing national hydrologic 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). Stahl *et al.* (2010) report on the assembly of a data set of gauging stations with RHN-type characteristics for Europe where national RHNs have not been designated (or at least not particularly promoted) in a majority of countries. Wilson *et al.* (2010) analyzed hydrological variables for a pan-Nordic network of gauging stations drawn from a Nordic version of the European Water Archive (EWA) (Roald *et al.* 1993). Rennermalm *et al.* (2010) explored trends in cold-season low flows for a pan-arctic network of gauging stations, where the stations were selected based on criteria similar to those used to define stations for a RHN. More broadly, the international FRIEND (Flow Regimes from International Experimental and Network Data) research programme of UNESCO has developed over 25 years to become a global network of research communities, operational hydrological agencies and policy makers to exchange and share scientific knowledge and data relating to trend detection, and to enhance capacity building in developing countries (Demuth *et al.* 2006).

The objective of the current article was to review and synthesize the development of RHNs from around the world based upon our collective national experiences; to assess the state of development and compare between networks; and to consider how to provide guidance for the future of these networks.

Why Reference Hydrologic Networks are necessary

Human dependence on water is fundamental and compelling, and hydrological data provide a necessary foundation for policy evolution and effective water management. Gauging station networks, to meet these information needs, generally evolved during a period when hydrological variability was considered to be around a relatively stable long term mean. This may no longer be true (Milly *et al.* 2008). The impact of climate change, and the likelihood that runoff patterns are changing over time, has major economic, societal, political, and ecological implications. Correspondingly, the focus of hydrologic data acquisition and stewardship needs to change to better reflect the overriding strategic need to index hydrological change more effectively, regarding several issues:

Hydrologic extremes.With water demand increasing, the equitable allocation of limited water resources, both within and between countries, will be essential if internal unrest and international conflict is to be avoided. In relation to engineering design, the economic costs of over-design, and the social implications of under-design, underline the need for appropriate mechanisms to reassess the risk of hydrological extremes (both high and low flows) in a warming world. For example, extreme high flows of defined risk are used to size bridge openings to safely pass flood flows while extreme low flows affect water supply, agriculture, and ecosystems.

Regional patterns. One of the main issues with climate change trend detection is that other, more direct, anthropogenic disturbances (such as water withdrawals, storage behind impoundments, and land-use change) may obscure the effects of climatic variability. Such anthropogenic impacts are prevalent in many parts of the world (Vörösmarty and Sahagian 2000). Döll *et al.* (2009) calculate that average river discharge and statistical low flow - Q_{90} (monthly river discharge that is exceeded in 9 out of 10 months) have decreased by more than 10% on one sixth and one quarter, respectively, of the global land area. Stahl *et al.* (2010) suggest that clearly identifying regional patterns of hydrological change has become one of the most important challenges in contemporary hydrology. Reliable information on such patterns, beyond the river basin or national scale, enables the identification and attribution of changes in flow regimes influenced by large-scale processes such as climate change. However, anthropogenic disturbances (e.g. abstractions, discharges and reservoir releases) have modified river flow regimes across the globe (e.g. Döll *et al.* 2009), confounding the identification of climate-driven changes.

Svensson *et al.* (2006) report that floods are of great concern in many areas of the world, with the last decade seeing major river flood events in, for example, Asia, Europe and North America. River flows calculated from outputs from global climate models often suggest that high river flows will increase in a warmer future climate. However, the future projections are not necessarily in tune with the records collected so far—the observational evidence is more ambiguous. A recent study of long time series of annual maximum river flows at 195 gauging stations worldwide suggests that the majority of these flow records (70%) do not exhibit any statistically significant trends (Svensson *et al*. 2006). Trends in the remaining records are almost evenly split between having a positive and a negative direction. Studies such as this suffer from not being focused on stations with the characteristics of RHNs, particularly with respect to climatic trends in the absence of other confounding human activities.

Hydrologic change can come from climatic changes as well as direct human influence from, for example, major dams, water withdrawals, or land use change. Examining hydrologic change that comes from changes in air temperature and precipitation requires relatively natural basins or basins with stable land use. It is important to understand how changing temperature and precipitation has and will affect streamflows—no matter whether the underlying causes are natural multidecadal changes or manifestations of climatic changes triggered by increased greenhouse gases. In recognition of this need, gauging station networks have been designated in several countries using the RHN criteria described previously, and largely capitalizing upon existing stations that met, or almost met, these criteria. In each country, the intention also was to reflect the hydrological variability of the country by ensuring that the predominant hydrologic types were included.

Much of the emphasis in RHNs to date has been focused on the monitoring aspects, and rather less on the analysis and interpretation. Many countries have been successful in developing these networks over the past decade, and scientists are increasingly becoming aware of the value of these networks for application in a variety of research activities. To this point in time, the development has been primarily focused on the collection and archiving of the data. While much remains to be done to address issues within existing networks the focus of these needs to broaden. We report here the results of a session, held in Quebec City, Canada in July 2010, to discuss the state and future of such networks; while the progress of developing and using these networks is commendable, we recommend changes in the next decade that will more fully capitalize on the large national investments in RHNs.

Usefulness of Reference Hydrologic Networks

Hydrologic networks generally serve several different objectives (Table 2). A companion paper (Burn *et al.* 2012) describes some case studies of RHN use in three countries. Data from RHNs have been used in many previous studies of trends in North America (e.g. Lins and Slack 1999 2005, Douglas *et al.* 2000, Zhang *et al.* 2001, Burn *et al.* 2010) and have recently found application in climate change attribution studies (Krakauer and Fung 2008). Stahl *et al.* (2010) reported that in North America, accounts of hydrological change have capitalized on reference river basin networks such as the US Hydro-Climatic Data Network (HCDN) of >1600 minimally disturbed catchments, or those that were considered to not have changed over time (Slack and Landwehr 1992), or the Canadian Reference Hydrometric Basin Network (RHBN) (Brimley *et al*. 1999, Harvey *et al.* 1999). Established RHNs have also seen extensive use for multiple types of hydrologic research. The streamflow data in RHNs are essential for calibration and validation of remote sensing data and climate models, as well as monitoring of trends and changes in the water system (Cihlar *et al.* 2000); in the calibration or validation of large- scale hydrological models (Lohmann *et al.* 2004, Troy *et al.* 2008); which can then be used to systematically study processes of change (e.g. Hamlet and Lettenmaier 2007).

Stations within RHNs are also useful for other purposes including their use on a comparative basis for assessing the impacts of changes in landuse with non-RHN stations, hydraulic change, and climate verification. RHNs also find wide application in the development, refinement and application of regionalisation procedures (e.g. Gustard *et al*. 1997, Cunderlik and Ouarda 2006) where streamflow characteristics are transferred from gauged to ungauged watersheds based on basin characteristics such as area and slope. Yoshitani and Tianqi (2007) suggest that PUB (predictions in ungauged basins) studies require an accurate set of discharge data, and flow data are almost always affected by withdrawals and returns. Stöll and Weiler (2010) examined rainfall-runoff modelling of ungauged basins using a new approach to guide hydrological modelling based on explicit simulation of the spatial stream network; the method was tested in four different catchments in Germany. Reference stream networks were then used to assess the output of this process-based model and the degree of spatial agreement.

The data have also been used for calculation of site ratios; the most basic method of infilling missing data starts with calculation of the long term ratio of each gauge catch to the mean catch of a reference network (Hudson *et al.* 1997). Sauquet *et al.* (2000) used data from 212 stations in the reference network HYDRO to model and validate monthly flow patterns in France.

Canadian Reference Network

The streamflow data from the Canadian RHBN have been used in more than 25 studies in the more than ten years that the network has been in existence. The studies have had a variety of purposes with the common feature being a desire to analyze streamflow data that can be considered to reflect near pristine conditions. The most common use of data from the RHBN has been for trend detection analysis (e.g., Zhang *et al.* 2001, Burn and Hag Elnur 2002, Yue *et al.* 2001, 2003, Cunderlik and Burn 2004, Hodgkins and Dudley 2006, Khaliq *et al.* 2008, Ehsanzadeh and Adamowski 2009, Burn *et al.* 2010). The trend analysis studies have differed in: the variables examined; the approach used to identify trends; and the scope of the analysis, with some studies being national in scope while others have examined specific regions of Canada. Several studies have used RHBN data to examine the variability of streamflow data or to investigate sensitivities to teleconnections (e.g., Coulibaly and Burn 2004 2005, Kingston *et al.* 2006, 2011, and Fleming *et al.* 2007). Other studies have used RHBN data to explore regional frequency analysis of extreme events (Yue and Wang 2004a, Yue and Pilon 2005). Finally, there have been studies that have examined other issues such as the scaling properties of Canadian streamflow data (Yue and Gan 2004, Yue and Wang 2004b) and the evaluation of statistical downscaling techniques (Whitfield and Cannon 2000).

United States Reference Network

The usefulness of streamflow data from the United States HCDN is best described by its use in published studies; the data from the HCDN have been used in more than 100 published studies since the network was created in 1992. Like the Canadian RHBN, the studies have had a variety of purposes. Unlike the RHBN, the most common use of data from the HCDN (about 40% of studies) has been for the analysis of a variety of statistical (e.g. Vogel *et al.* 1999, Reilly and Kroll 2003, Saunders *et al.* 2004, Watson *et al.* 2009) and deterministic (e.g. Gordon *et al.* 2004, Pagano and Garen 2004, Hamlet and Lettenmaier 2007, Wenger *et al.* 2010) models for issues such as flood risk, water supply, and aquatic ecosystem health. Temporal trend analyses have also been common, comprising about 30% of published studies based on HCDN data; studies have been completed at national (e.g. Lins and Slack 1999, McCabe and Wolock 2002, Krakauer and Fung 2008) and regional (e.g. Regonda *et al.* 2004, Small *et al.* 2006, Brutsaert 2010) scales, as well as international ones (e.g. Stewart *et al.* 2005, Hodgkins and Dudley 2006). Flow trends, like flow models, are important for various reasons, and the trend studies analyze various relevant flow metrics for annual or seasonal flows. HCDN data have also been used to analyze teleconnections between streamflows and various large scale atmospheric circulation and sea surface temperature indices such as ENSO, PDO, PNA, AMO, and/or NAO (e.g. Cayan *et al.* 1999, Rogers and Coleman 2003). Other uses of USGS HCDN data include analyzing the geographic variability of streamflows (e.g. Lins 1997, Peterson *et al.* 2000) and statistical properties of streamflows (e.g. Vogel and Wilson 1996).

United Kingdom Reference Network

In the United Kingdom, the national Benchmark Network (around 90 well monitored catchments) provides the core capability for hydrological trend detection and appraisal. It is a key component in the United Kingdom climate change detection programme (Cannell *et al*. 2004) and has found wide application in related United Kingdom and European studies of changing runoff patterns (Hannaford and Marsh 2006, 2008, Stahl *et al.* 2010). The Benchmark Network has found wide national and international application in relation to trend detection and has been exploited in United Kingdom Climate Change Indicator programme and also other related research topic areas.

Close collaboration between the United Kingdom National River Flow Archive personnel and their counterparts in the Measuring Authorities has resulted in the development of a series of network and data appraisal mechanisms over the last decade. Their aim is to maximise the utility of the river flow series in the United Kingdom Benchmark Network and provide an information base which underpins a capability to identify and interpret hydrological trends. Many of these mechanisms have been formalised in Service Level Agreements; some form the basis of proposed changes in British and European hydrometric data processing standards.

Operational Experience with National Reference Hydrologic Networks

In the design and evolution of these networks, stakeholder involvement, national strategic objectives, impacts of artificial influences (landuse, storage, diversion etc), hydrologic network operational performance requirements, and synergistic or complementary benefits of co-ordinated hydrometeorological monitoring all need to be considered. In reality, many of these aspirations have had to be relaxed to attain a future objective, that being that the network should be representative of the hydrologic variation that exists in a particular country (Stahl *et al.* 2008). In addition, hydrologic data collection is inherently challenging (particularly in the extreme flow ranges), and data quality issues – such as inhomogeneities resulting from rating changes or underestimation of high flows due to bypassing of gauging stations – can induce spurious trends that bear little relation to climate variability. Each of the national RHNs has had a different development and operational experience. The following section describes these different experiences in Canada, the United Kingdom, and the United States.

Canada

In Canada, a partial review carried out in 2010 (K.D. Harvey, *personal communication)* of the original stations identified as being part of the Reference Hydrometric Basins Network (RHBN) revealed that roughly 60% of them still met the first five of the above-mentioned criteria. Actually, 79% were in a pristine basin, 92% were not affected by control structures, 90% did not include poor or unacceptable quality data and 93% were still active. However, some of the stations were decommissioned at some point in their history, causing discontinuities in the records. Including stations that do not comply with all the criteria has sometimes been done on purpose, as long as the overall effect on the quality of the network was deemed minor. While allowing some flexibility in the definition or application of criteria results in potentially increased spatial coverage, the extent to which data are then suitable for the intended purpose can be debated. As such, any derogation to the theory should be extensively documented and justified in the metadata, which has to be widely available to end users. This has unfortunately not been done systematically in the original RHBN, but improvements are expected in this regard in the future.

Another issue related to the application of the criteria for the RHBN is the lack of objective methods for the application of systematic, consistent criteria throughout the country. The qualitative nature of some criteria (ex. data quality) and the wide hydrological variability in the many diverse systems of Canada requires local experts to judge whether a specific criterion is met or not. However, this results in decisions regarding stations that can be difficult to justify to decision-makers or RHBN users. This emphasizes furthermore the need to fully document the process of criteria assessment and make that documentation available to users, as well as the need to develop objective methods in collaboration with the operational people.

Finally, there is a need for a systematic, periodic review of the network to keep records up to date, to add or remove stations relative to their compliance with all criteria and to inform users of any updates performed. Partial, annual reviews could be conducted to assure a general maintenance on the network, and a more comprehensive review could be conducted say every decade to identify major changes (such as basin development) and assess the effectiveness of the network. These reviews would also be helpful in identifying gaps in the coverage, as well as new stations that have the potential to be part of the network in the future (i.e. not 20 years of data yet, but other criteria met) to help justify keeping them active to sponsor organizations.

While the Canadian RHBN has been used in a number of studies, there are limitations to the present network. The spatial distribution of the stations is not uniform with fewer stations in the north than in the south. In addition, many of the more northerly stations are for larger watersheds and have shorter record lengths. The predominance of larger watersheds in the north limits the capability of examining the hydrological response in small watersheds and the short data records makes trend detection a severe challenge in the north. In the time that the RHBN has been in place, some of the stations have been discontinued, raising concerns regarding the commitment to the RHBN as a reference network. Finally, metadata for RHBN stations are not readily available, which does not allow for the exploration of why unusual results may have occurred.

United Kingdom

A preliminary attempt to designate a United Kingdom representative basin network was undertaken in the 1980s (Lees 1987) but a strong focus on hydrological trend detection awaited the convening, in 1999, of a national symposium to determine strategic hydrometric information needs for the 21st century (Marsh 2002). This provided a blueprint, supported by all the primary stakeholders, to establish an enhanced capability to identify climate-driven changes in UK river flow regimes. To this end, an initial Benchmark Network was established in 2002 (Bradford and Marsh 2003) and, after a review of time series quality and continuity, and the use of more advanced catchment descriptors to assess the representativeness of candidate catchments (Laize *et al.* 2008), a revised network of around 90 catchments was designated. The average record length is approximately 35 years with many of the selected stations being commissioned in the 1970s. The latter was a notably dry decade and to help assess the influence of climatic variability on long term trends, a complementary selection of long time series (>50 years) was made.

In parallel with the designation of the Benchmark Network, a review of the data acquisition and archiving procedures was undertaken and enhanced validation procedures were agreed with the UK Measuring Authorities: the Environment Agency in England and Wales, the Scottish Environment Protection agency in Scotland and the Rivers Agency in Northern Ireland. Support of the latter has been critical to the success of the Benchmark Network and despite continuing pressures caused by a burgeoning operational need for hydrometric data (e.g. relating to additional flood warning provision), the MAs have agreed that no Benchmark station will be decommissioned without consultation with the Centre for Ecology & Hydrology.

The impact of artificial influences on natural flow regimes is pervasive across much of the UK. This is particularly true of eastern, central and southern England where concentrations of population, intensive agriculture, and commercial activity make for the greatest water demand. Thus some degree of regime disturbance is inevitable and comprehensive metadata are essential to help index and understand the net impact on the flow regime. In hydrologic terms, considerable effort is devoted to maximizing the homogeneity and continuity of the river flow time series incorporated in the Benchmark Network (Harvey *et al.* 2012), particular attention being directed to flows in the extreme flow range. Successful data stewardship requires continuing vigilance and productive liaison with the MAs.

Rigorous validation and data review procedures have demonstrated that only a proportion of the Benchmark Stations have high quality (and homogenous) time series for both the highest and lowest flow ranges. Consideration is therefore being given to the designation of complementary low and high flow benchmark networks.

United States

A subset of USGS streamflow gauging stations was identified in 1992 (Slack and Landwehr 1992) that had historical streamflow data responsive to climatic variations (relatively free of confounding anthropogenic influences such as dam storage, regulation and urbanization). All of the data in the HCDN have been collected and quality assured by a single Federal agency—the USGS—since the start of data collection; consistent and well documented procedures have been used (e.g. Corbett *et al.* 1943, Rantz *et al. 19*82).

The HCDN was designed to meet the criteria, specified earlier in the current article, of low basin development, absence of significant regulations or diversions, minimum record length criteria, and data accuracy—with the following caveats (Slack and Landwehr 1992). The appropriateness of stations for the HCDN was primarily determined by USGS State offices who have been responsible for the historic collection of streamflow data in their state and have extensive local knowledge of the quality of data from gauging stations and of the basins they drain. The degree of basin development was based on local knowledge rather than quantitative basin land cover percentages. Significant regulation and diversions have been historically documented, quantified, and published for stations; these stations were not used for the HCDN. Some stations with unchanging diversions over the period of record and some stations with low head dams that have only a transient effect on streamflow were included in the HCDN. The minimum record length for stations was generally 20 years through 1988, but some stations with less than 20 years were allowed in under represented areas. Station density is lower in some parts of the western United States than in other parts of the United States. Stations were included in the HCDN if they were not active, but had at least 20 years of data that met the various criteria for inclusion. The predominant accuracy of streamflow records had to be "good" quality. Data quality at all USGS stations is rated and published annually. This rating reflects the professional judgment of the office that collects the data and depends on the accuracy of stage measurements, the stage/flow relationship, and the accuracy and frequency of flow measurements. A quality rating of "good" implies that 95% of daily mean flows are assessed to be within 10% of true values.

The HCDN has not been systematically updated since its inception and data collection at some stations has been discontinued. Some stations may have experienced increased development in that time or may have become inappropriate for the study of climatic variations for other reasons. More than 20 years of data have been collected at existing and new gauging stations in the U.S. since the HCDN was created and additional stations appropriate for the study of streamflows that are responsive to climatic changes exist that are not in the HCDN.

In a related development, however, the USGS has recently completed a quantitative analysis of gauged drainage basins to establish reference basins in the conterminous United States (Falcone *et al.* 2010), primarily for determining natural streamflows relevant to aquatic ecosystems and for evaluating natural versus altered flow conditions. The resulting database, referred to as GAGES (Geospatial Attributes of Gages for Evaluating Streamflow), incorporates basin attributes for 9324 USGS streamflow gauges, and their upstream drainage basins, that have complete-year flow record from 1950-2009. These basin data include the percentage of basin area that is urban, agriculture, forest, open water and wetland, and impervious surface; historic and recent population density; soil types; dam storage; and freshwater withdrawals in the basins. Some 2061 gauges were identified as reference stations least affected by direct human activities. For a gauged basin to receive a reference designation, it had to meet three primary criteria: (1) There had to be less hydrologic disturbance in its watershed than at least 75 percent of all other gauged watersheds in its ecoregion. Watershed hydrologic disturbance was quantified with an aggregate index that included geospatial measures of reservoir storage, dam locations and density, freshwater withdrawal, road density, and National Pollutant Discharge Elimination System (NPDES) discharges. The disturbance index was calculated for all gauged watersheds and ranked within each of nine major ecoregions. Gauged sites whose watersheds were in the lowest quartile of the disturbance index were given priority consideration as potential reference quality. (2) It was not identified as having "regulated" streamflows in the Remarks sections of the most recent USGS Annual Data Reports. Some sites considered to have "minor" modifications were retained. (3) It passed a visual screen using satellite imagery (typically Google Earth), which scanned the entire watershed for the presence of human activities that suggested flow diversions, groundwater withdrawal, and other factors known to influence natural streamflows.

In addition, the selection of reference sites was not limited to a specific attribute of the flow regime. For example, human activities in a basin may have no net impact on mean annual flow but, nevertheless, influence the timing and duration of specific flow magnitudes. Under such conditions, the site would be excluded. The intent was to identify gauged sites with all attributes of the streamflow regime in natural or least-disturbed condition. Also, for gauges with some amount of irrigated agriculture in the watershed, USGS determined whether the irrigation withdrawals were sufficient to alter streamflows by examining observed monthly flows (over the last 10 years of record) relative to monthly flows expected using a water-balance model. If observed monthly flows during the irrigation season (May-September) were substantially less than the expectation of the water-balance model, the gauge site was excluded from consideration as reference.

Of the 2061 stations receiving a reference designation, 1637 had at least 20 years of continuous record ending in 2009. Given the close correspondence between HCDN and GAGES Reference criteria, with the latter being generally more stringent than those originally established for the HCDN, USGS decided in 2011 to use the 1637 Reference stations having 20+ years of record as the updated HCDN. Those stations are now designated as "climate sensitive" in the GAGES database. In so doing, the USGS avoided potential conflicts arising from publishing competing reference quality station listings.

Common Network Issues

When comparing existing RHNs a series of issues were identified that are common to most existing networks. Solutions to these common issues are perceived to be broadly beneficial. The common network issues include: (a) Adequacy of networks for change detection; (b) Access to data, metadata, and watershed information; (c) Harmonization within and between networks including policies, quality control, data formats, coding and transmission; (d) Data integration including both data from different networks [e.g. hydrologic, climatic] as well as multiple platform observations [e.g. ground-based and remote sensing]; (e) Generation of research and applications-oriented products; and (f) Lack of metadata on landuse and landuse change.

Harvey and Grabs (2003) argue that data collection and management activities are typically undertaken at the national level, but there is a need for internationally-coordinated regional [spanning neighbouring countries] systems. Smaller countries in particular benefit from supplemental information from these types of regional sources, especially neighbouring countries. Regional projects are driven by region-specific requirements for data and information. The river basin, rather than political boundaries, needs to be considered as the appropriate geographical unit for regional-scale hydrologic monitoring activities. The challenges common to most regions include inadequate monitoring networks; gaps in the records; a general decline in the number of stations; chronic under-funding; differences in processing and quality control; and differences in data policies. Political and technical challenges differ from region to region. Major problems in the poorer regions of the world include poor status or outright lack of monitoring networks and support infrastructure, especially in Africa, and data quality problems.

One issue relevant to many countries and regions is whether similar sized catchments should be used for trend studies. Some researchers advocate selecting only those gauging stations with a drainage area within a defined size range to avoid unique responses being masked by larger catchment areas or for other reasons (Stahl *et al.* 2010, Woo *et al.* 2008). However, applying restrictions on the acceptable catchment size can result in a considerable reduction in the number of available gauging stations for an RHN. While standardizing based on catchment area is not always beneficial, it is clearly important that scale issues are addressed for trend studies, particularly those relevant to water management. In many countries, RHN catchments are necessarily small, by virtue of the fact that small, headwater catchments are those least likely to be disturbed. RHN studies therefore contrast with many other trend studies carried out on large, disturbed basins (typically those held on the GRDC; e.g. Milly *et al. 20*05, Dai *et al. 20*09). Stahl *et al.* (2010) note differences between headwater catchments used in their study and results from other studies which use stations at the catchment outlet (e.g. the Danube, cf. Stahl *et al. 20*10 and Dai *et al. 20*09). The reason for this may be due to human disturbances, but it is also important to note that different hydrological processes operate across a range of scales (Blöschl and Sivapalan 1995) and climate change may cause differing responses at different time and space scales. Given that RHN stations in many countries will necessarily be small headwater catchments, it is important to also consider scalability of results; headwater catchments, while perhaps more sensitive to climatic variability, may not be representative of larger scales relevant for water management, so there is some argument for considering results from RHNs in the context of results from large catchment studies or using runoff from large regions, as carried out in the UK studies (Hannaford and Marsh 2006, Hannaford and Harvey 2010), and other studies which compare small, unregulated catchments with larger, but more disturbed, catchments; e.g. Lindström and Bergström 2004).

Future Directions

RHNs have made a major contribution to hydrological trend detection and interpretation over the last 15 years and have also served to emphasize the complexities in the association between climate change and the impacts on river flow regimes. However, operational experience has demonstrated that issues remain to be addressed if RHNs, individually and collectively, are to effectively meet the strategic needs of policy makers. At the Quebec City workshop a group met to discuss where we presently are with the development of RHNs and to ask the question of “where do we need to be in 10 years?” The urgent need to quantify and understand hydrological change underpins the need for the designation and maintenance of

RHNs. The results of those discussions are reported herein; discussions of each category follow the list of categories. In general terms:

1. RHNs should clearly demonstrate "fitness for purpose".
2. Users need to have access to tools and documentation to support proper use of these time series. Users should have better access to both the technical documentation of individual countries and WMO, but also to the collection of scientific literature that deals specifically with trend detection using national and international reference networks.
3. More specific guidance on how to best use reference stations and networks should be commonly available and used. Guidance that is available is often too general and lacks applicability.
4. Development and promotion of enhanced network review mechanisms and data validation/stewardship protocols for the time series associated with RHNs should be completed.
5. The particular importance of long river flow series from non-RHN gauges in providing a broader temporal context within which to assess the trend evidence deriving from RHN analyses should be recognized.
6. Hydrologists from a variety of countries should work together to develop a subset of the international networks that are representative of the hydrologic variation of the Earth and to develop a consistent way of analyzing and presenting them.
7. A range of dissemination mechanisms should be exploited to ensure that the data and analytical outcomes of RHN programmes are accessible to all stakeholders.
8. Monitoring and analysis communities need to work together.

Reference Hydrologic Networks demonstrate "fitness for purpose"

Harvey and Grabs (2003) suggest that the technical challenges related to collecting, managing and accessing global datasets – and ensuring proper quality control – can be met by employing current and emerging technology and standards, best practices and available infrastructure. Metadata are a very important component not only to describe the data, but to provide a useful contribution to the data quality assurance procedures (Harvey and Grabs 2003). Steps need to be taken to support the credibility of data being collected in reference networks to ensure that users can be confident that the data are indeed suitable for the intended purposes (Whitfield 2012):

- A clear statement of the reason the data were collected. Were the data collected with any thought of long-term requirements?
- Proper documentation of the complete location and operation history. When did instruments, observing practice, locations, sampling frequency change during the collection of this record?
- Proper documentation of changes in the data workup that have taken place during the collection of this record.
- Access to support data: rating curves, meter calibrations, measurement validations and maintenance records sufficient to support confidence in the data.
- Ability to “verify” observations in the record; perhaps by having access to stage observations and stage discharge relationships.
- Ability to “verify” the record against process similar records, for example compare with similar records in the vicinity.
- Documentation of watershed change, including landuse.
- Creation of data management systems which are sufficient to protect the integrity of the data.
- Creation of common interchange access format that supports sharing. Web services are becoming increasingly available to facilitate access to data from distributed and disparate sources.

Stahl *et al.* (2010) suggest that the update and data collection require the help of many national or regional agencies responsible for collecting streamflow data in individual countries, as further described in Stahl *et al.* (2008) and Hannah *et al.* (2011). Their criteria were:

- Homogeneous, quality controlled records of daily mean flow;

- Suitability for low flow analysis, including no appreciable direct human influence on river flow during low flow (e.g. through abstractions, reservoir storage);
- Small catchments with areas generally not exceeding 1000 km^2 were the main focus; however, some slightly larger basins were included, where there was a significant justification for improving spatial coverage;
- Time series should cover 40 years or longer and include recent data.

Tools and documentation support proper use of RHN time series

There is general agreement that users need better tools and documentation that supports assessment of integrity, homogeneity, and coherence of these time series:

- Better access to support data. Software that links to changes in methods, station metadata, that clearly identifies possible non-homogeneities including common flags associated with these data (backwater, estimated, infilled).
- Information from rating curves supporting assessments of uncertainty at all water levels.
- Documentation of measurement technologies such as meter calibrations allowing for retrospective assessments of methodologies.
- Development of methods for measurement validations including estimation methods and infilling methods.

The clear intention here is to have information available that is sufficient to support confidence in the data, at present and in the future. There is great potential for adopting the use of common diagnostic software.

Guidance on how to best use reference stations and networks

Users of reference network time series and tools need to know more about how to use these materials. It is important to provide guidance on how reference stations can/should be used in developing a broader study. There is a need for specific guidance on how reference stations can be used in comparison with other stations, such as how to build a hypothesis on results from analysis of RHN data, or how to compare with results from other non-RHN datasets to assess a climate signal in relation to other change signals.

In some circumstances flows from pristine areas will not be available. Alternatives that might be considered include a requirement that flows be naturalized. Because not all watersheds are ‘pristine’ can we develop a method to describe ‘naturalness’? Such an indicator might be used to weight assessments; perhaps weighing ‘pristine parkland’ with more weight than lands in other states of development.

For some catchments, particularly where there is a predominant, and measurable, artificial influence on the natural flow regime, daily or monthly naturalized series can be of considerable strategic value. The River Thames provides a revealing example: annual mean gauged flows have reduced considerably over the 128-yr record but (non-returning) abstractions from the Thames have increased by an order of magnitude since the 1880s and, once allowed for, the naturalised series exhibits a significant positive trend (Marsh and Harvey in press).

Generally, the quality of reconstructions particularly of natural processes is difficult to achieve. A method to indicate the degree of naturalness, or the success of reconstruction, should be developed to allow better comparisons between various types of data series – pristine, near natural, agricultural etc.

There should be a common interchange access format that supports 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 have tools to interact with their national data and international data without translation.

Develop and promote enhanced network review mechanisms and data validation/stewardship protocols for the time series associated with RHNs

There are currently few if any rigorous guidelines for network review and evaluations. Rigorous application of validation procedures and professional data stewardship and analysis are essential if the considerable investment in the networks is to be properly reflected in improved water management and policy frameworks (Marsh 2002). In turn, this implies a continuing dialogue with stakeholders to ensure: priority strategic needs are being addressed; and relevant datasets, reports and scientific papers are widely disseminated.

Recognize the particular importance of long river flow series from non-RHN gauges

There is a consistent need for long records to support detection of change and for assessing the linkages between climate and streamflow. The long-term climate signal is complex and regionally contains not only the signal of anthropogenic climate change, but also many features of the climate signal including but not limited to NAO, PDO, and ENSO. Separation of these signals and their effects on hydrology depends upon the availability of long time series of observations. There are long records (> 50 years) available for many catchments in North America with little direct human influence, but few in some developed parts of the world. It is important to maintain long records in these developed areas, even if they are directly influenced by human activity. While separation of the climate signal and the direct human signal is not always easy, these data are valuable.

Hydrologists from a variety of countries should work together to develop a subset of the international networks that are representative of the hydrologic variation of the Earth and to develop a consistent way of analyzing and presenting them.

Cihlar *et al.* (2000) suggest utilizing hydrologic observations that are particularly important for global change impact studies. This would include daily runoff series for a few hundred small natural catchments (~1000 km^2 in size) distributed over the globe from a wide variety of climatic, topographic, and ecological regions, together with precipitation and other data permitting the study of hydrological processes in specific regions. Multiyear groundwater, surface water and water use time series would help characterize water availability in these catchments and surface water flux values would be computed to anticipate change in storage in natural reservoirs. While RHN data from similar sized catchments are needed for comparative studies, there is also a need to have a variety of size basins to address scaling issues. Because climate influences on streams occur at the landscape level, assembling a variety of case studies with different periods of data, with different methods, in different landscapes is neither simple nor does it provide the needed clarity.

There is a need to use consistent data, analyses, and presentation of results to overcome the apparent confusion of the collected past studies from different regions that are not consistent. The suggestion is that we support a collaborative effort that routinely updates analyses of how the hydrology of catchments in the proposed international network respond to the climate system. We are seeking to best understand how these rivers respond to important regional climate signals and to separate effects of natural climate variability from climate trends related to increased greenhouse gases, to support correct attribution. We also seek to separate landscape and landuse signals from those of climate by comparing reference stations to non-reference ones, recognizing the opportunity for interactions to exist between climate and landuse signals.

Develop dissemination mechanisms to ensure that the data and analytical outcomes of RHN programmes are accessible to all stakeholders.

One of the issues with RHN programs is that the data suitable for analysis and interpretation are not readily available. Each country distributes data in a format that suits its needs. While GRDC does distribute data that are shared with them, much of what might potentially be available is not in their databases (Table 1). There are several possible solutions to the current situation, but having a standard format for distributing the data and metadata would be a first step. Many of the existing formats provide backward compatibility for each country, and continue formats that were more a product of efficient storage than ease of use. Development of this format should also consider the existing initiatives for internet access such as WaterML 2.0. These initiatives seek to standardize water information and help with the difficulty of exchanging or collating water information and data; they also offer the potential for exchanging surface water, groundwater and climate data more effectively. Similarly, analysis and interpretation software that could be shared amongst researchers, and reading data from that common format, would greatly enhance the analysis of data on an international scope as much less time could be devoted to data acquisition and preparation and more time invested in analysis and interpretation.

Summary

We are suggesting an informal International reference hydrologic network that is representative of the hydrologic variation of the earth, seeking to have high quality, well documented data from similar sized natural catchments from a wide variety of climatic, topographic, and ecological regions. This would involve the monitoring and analysis communities working together more closely and would allow scientists to get a global picture of climate related hydrologic changes, while respecting that water is a local issue for decision makers. This larger scale can help identify 'clusters' of similar response to climate and then help us focus on regions to explain at that scale. This is expected to lead to a more organized 'drilling' into the details. At the same time, many small countries depend on the global community for techniques, training and shared experience. One identified opportunity was to support the development of a specific global hydrologic reference network data set that could be used for assessments based on common data. There is a clear need for a reference hydrologic dataset appropriate for global climate studies. Subseries of that dataset could be used for local reference; for example it would be useful to compare reference network series to non-reference ones to detect land use change. The dataset should contain catchments both a diversity and commonality of scales. Countries would be encouraged to contribute a limited number of stations with appropriate metadata, instead all of a nation's data. We recognize that we need to look to the original sources where possible as the National authority is always most relevant. There is a need and an opportunity for one international agency to take on the role of contributing support and facilitation for the above.

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Table 1. Attributes of the existing reference hydrologic networks from 22 countries.

Country		**Number of stations**	**Climate specificity**	**Minimum record length reported to WMO/GRDC (Years)**	**Data available at GRDC**	**Comments**	**Reference**
Australia		31	Yes	>38	Daily All data	Good quality recent records from Benchmark Sites (BMS) and “Wild River” (WR) stations	
Azerbaijan		14		10	Daily 1 Station	Data for 1 station from 1978 -1987	
Belarus		10		>30	No		
Brazil		238	Yes	>23	Daily All data	Recent data from identified stations	
Brunei		None			No	No stations meeting criteria	
Canada	RHBN	229	Yes	(>30) 20	Daily 150 Stations	Good quality recent data from 150 of 229 RHBN stations	Harvey *et al.*
China		15		20	Daily All data	Data only up to 2000 submitted to GRDC	
Cyprus		4		>22	No	No discharge data for identified stations submitted to GRDC	
Czech Republic		6		>40	Daily 1 Station	Recent data for 1 station	
Ecuador		6		>23	Daily 1 Station	Data for 1 station up to 2005	
Finland		12		>25	No	No discharge data for identified stations submitted to GRDC	
France	HYDRO	212			No	Some data are	Sauquet *et al*

						reconstructed, no stations reported to GRDC	2000
Georgia		8		>30	Daily 1 Station	Data for 1 station up to 1987	
Japan						Reconstructed data, no stations reported to GRDC	
Kenya		60		>26	Daily 1 Station	Data for 1 station up to 1980	
Kyrgyzstan		7			No	No discharge data for identified stations submitted to GRDC	
Lithuania		7		>20	No	No discharge data for identified stations submitted to GRDC	
Mauritius		2		>30	No	No discharge data for identified stations submitted to GRDC	
Morocco		12		>30	Daily 1 Station	Data for 1 station up to 1987	
Pakistan		6		>25	Monthly 1 Station	Data for 1 station up to 1979	
Romania		23		>35	Daily 4 Stations	Recent data for 4 stations	
Slovakia		20		>70	Daily 2 Stations	Data for 2 stations up to 2001	
Sweden		7	Yes	>30	Daily 7 Stations		

Switzerland		8			No	No discharge data for identified stations submitted to GRDC	
Switzerland	SRHN	231 (6)		>30		No reference to this network at GRDC	
Tajikistan		23			Daily 4 Stations Monthly 8 Stations	Data for 12 stations up to 1990	
Ukraine		3		>45	No	No discharge data for identified stations submitted to GRDC	
United Kingdom		20			Daily 16 Stations	Recent data from identified stations	
United States	HCDN	1703			Daily 410 Stations	Good quality recent data from 410 of 1703 HCDN stations	
Uzbekistan		6		>35	Monthly 1 Station	Data for 1 station up to 1995	
Western Samoa		2		>30	No	No discharge data for identified stations submitted to GRDC	

Table 2. Network Monitoring Objectives

Category	**Main objectives**
Reference	Identify and interpret hydrological trends principally climate-driven
Environmental Impacts	Monitor heavily impacted catchments to establish the degree of disturbance (anc monitor remedial measures)
Regionalisation	Underpin the development of regionalisa techniques and modelling procedures
Integrated Monitoring	Provide a focus for the improved understanding of hydrological processes from the sub-catchment to the basin scal
Transboundary	Monitor flow that cross between political jurisdictions [National, International]