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An evaluation of hydrometric monitoring across the Canadian pan-Arctic region, 1950–2008

Theo J. Mlynowski, Marco A. Hernández-Henríquez and Stephen J. Déry

ABSTRACT

This study evaluates the hydrometric monitoring maintained within the Canadian pan-Arctic and is based on the hydrometric gauges closest to northern seas for 76 river systems throughout 1950–2008. Monitoring is quantified by compiling time series of total gauged area and discharge values from the available hydrometric records. We further evaluate the quality of hydrometric data by examining the availability of hydrometric records, the continuity of individual records, and the influence of water regulation on river systems. The maximum gauged area of the Canadian pan-Arctic was 64% in 1990 before it slowly decreased to 56% in 2008. Larger river systems typically had the most hydrometric data available, though each river system had an average of 46% of their records available. In 1998, a maximum of 22 river systems had more than 30 years of continuous records, which is the maximum attained throughout the study period. For future improvements in hydrometric monitoring, additional gauges on relatively small rivers will need to be deployed. We suggest new gauges should be implemented in the Eastern Hudson Bay, Ungava Bay and Labrador Sea basins in spite of the tremendous need for more in the Arctic Archipelago.

Key words | hydrological cycle, hydrometric monitoring, international polar year, northern Canada, pan-Arctic, river discharge

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INTRODUCTION

Rivers are natural pathways for water to flow from the land surface and into oceans, inland seas, and lakes. Collectively, climate (e.g. precipitation, surface air temperature), catchment size, landscape characteristics (i.e. geological and ecological), and anthropogenic disturbances (e.g. hydroelectricity developments, irrigation practices) influence river runoff rates. If any of these controlling factors are altered, river discharge will respond. Thus, river discharge is a sensitive component of the hydrological cycle as it links the atmosphere, land surface, and oceans, making it the only variable that integrates hydrological processes over space (i.e. the river basin; Mason *et al*. 2003) and time. Because of these integral connections, climatic and environmental processes on the landscape can easily be monitored with hydrometric gauges on river networks. For example, rather than having a vast array of in-situ precipitation gauges, one hydrometric gauge can be used to calculate the net precipitation across a drainage basin. These hydrometric gauges are especially important to societal needs as they are valuable tools for flood forecasting and hydroelectricity management, among others. In addition, hydrometric gauges are especially vital for understanding the possible links that exist between the variability in the hydrological cycle of a region and its changing climate (see Déry *et al*. 2009). Moreover, according to Mitosek (1992), river flows are the most suitable variable for monitoring climate conditions. This is why it is important to have a good hydrometric measurement network to detect and track these changes.

There is little doubt that hydrometric data are essential to society, but in recent years the combination of harsh environmental conditions, lack of infrastructure, and the redirection of government priorities and funds have made it increasingly more difficult to monitor river discharge,

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particularly in northern Canada (Grabs et al. 2000; Shiklomanov et al. 2002). As a consequence of these setbacks, we should be asking ourselves whether there is sufficient hydrometric monitoring to satisfy societal and scientific needs, and how can this monitoring be evaluated? In fact, a number of studies have already examined some of these issues (e.g. Scott et al. 1999; Lammers et al. 2001; Shiklomanov et al. 2002). Generally these studies have focused on the density and number of hydrometric stations (Shiklomanov et al. 2002) or on the 'age' of the active stations within a region over time (Lanfear & Hirsch 1999). Burn & Goulter (1991) and Mishra & Coulibaly (2009, 2010) contributed to this research by identifying essential and redundant streamflow stations in portions of Canada's hydrometric network as well as identifying critical areas where additional stations could be deployed. These types of studies are appropriate for small-scale water management issues (e.g. flood management), but are not necessarily useful for examining large-scale environmental changes (e.g. quantity of discharge reaching the oceans). For large-scale studies examining total discharge, only one gauge per river is essential, with this gauge being the one closest to the river's outlet. It is the outermost gauge that is critical for assessing and monitoring freshwater flow to the world's oceans (e.g. Dai & Trenberth 2002; Milliman et al. 2008).

Monitoring of rivers in northern latitudes is of the utmost importance because these rivers have the potential to affect the biological, chemical, and physical properties of the Arctic Ocean (Shiklomanov et al. 2000; Vörösmarty et al. 2001). The Arctic Ocean, in comparison to other oceans, is unique as it is the most land-locked (Vörösmarty et al. 2001) and shallowest (Jakobsson 2002). It also receives a disproportionate amount of the total global runoff (≈11%) compared to the total ocean water volume (1.2%; Shiklomanov 2000). Owing to these attributes, the influence of river runoff into the Arctic Ocean is more pronounced. This emphasizes the need to define river contributions to the Arctic Ocean and determine how those contributions are being monitored.

In Canada, an estimated 60% of the total river discharge flows to northern latitudes contributing to 4.2% (≈1987 $km^3 yr^{-1}$) of the world's renewable water supply (Environment Canada 2006). This large discharge contribution highlights the need for adequate hydrological monitoring; however, the network of hydrometric gauges on these rivers has yet to be fully quantified and evaluated. Thus the goal of this study is to evaluate the monitoring of river discharge in the Canadian pan-Arctic, 1950–2008. We do so by compiling time series of hydrometric data for 76 rivers located within Canada that have their outlets in the pan-Arctic region. Our primary goal is to objectively quantify and evaluate Canada's hydrometric monitoring by using a river's gauged area and discharge. A secondary goal is to examine the quality of hydrometric monitoring by scrutinizing the availability of hydrometric records, the continuity of individual records, and the influence of water regulation on rivers (e.g. Kingston et al. 2006).

BACKGROUND

Canada's hydrometric network commenced in the 1890s, in Alberta and Saskatchewan, as a means to develop irrigation plans. Surface water monitoring slowly expanded to all provinces (ca. 1922), all territories (ca. 1944), and Newfoundland (ca. 1950) as it became increasingly necessary for the continuation of economic development (e.g. irrigation, industry, municipal water supply and hydropower; Scott et al. 1999).

During the period 1910–1930, the total number of active hydrometric stations within Canada increased from 100 to 600; however, the network declined by approximately 28% in the 1930s due to economic challenges (Scott et al. 1999). By the late 1950s, the network had expanded to 1250 stations, followed by a subsequent expansion to 3000 stations by 1975 (Scott et al. 1999). In 1971, under the Canada Water Act (1970), Environment Canada was mandated to: (1) provide program management; (2) develop national standards for data collection, hydrological methods and database management; and (3) incur the costs for publishing all data collected according to national standards (Scott et al. 1999). Data that were collected by a third party and met the federal standards were also to be included in the national hydrometric database (HYDAT). Shortly thereafter in 1975, the Federal–Provincial Cost-Share Agreement was formalized to ensure a viable and efficient national water quantity monitoring network through the following principles: (1) harmonization, (2) cost-sharing,

(3) common methods and procedures, (4) accurate and timely data, and (5) open and free access to data (Scott *et al*. 1999). The costs were initially considered a 50/50 shared responsibility between the provincial and federal governments; nonetheless, the federal funded portion has significantly declined over the past four decades (initially 60% in 1975, then 48% in 1989, and 41% in 1999; Pyrce 2004).

Canada's entire hydrometric network peaked at 3417 operational hydrometric stations in 1984 (Scott *et al*. 1999), but has since downsized to 2862 hydrometric stations in 2008 as a result of the budget pressures in the 1990s (http://www.ec.gc.ca/rhc-wsc/2009). Higher perceived priorities in areas with larger populations and more operational needs have left relatively few stations to cover the broad territorial expanse extending north of 60 °N (Scott *et al*. 1999). The harsh environmental conditions and lack of infrastructure in high latitudes hamper the establishment, operation, and maintenance of hydrometric stations (Grabs *et al*. 2000). This typically increases the operational costs by three to four times the rate of those stations located in the south (Scott *et al*. 1999).

STUDY AREA

Our study area, the Canadian pan-Arctic, is defined geographically by rivers flowing into high-latitude oceans, and politically by the hydrometric gauges established within Canada. The Canadian pan-Arctic region covers an area of 8.23×10^6 km^2 or more than three-quarters of Canada (Figure 1). This region is further characterized by mountains in the west, dry prairies in the central interior, cool-wet boreal forest in the mid-latitudes, and tundra in the north. An estimated 85% of Canada's population can be found in the south where there are more favorable environmental conditions (Environment Canada 2006), leaving communities in the north to be few and far in between.

Within the study area, we further grouped rivers into six regional drainage basins (referred hereafter as regional basins) that are identified by the main body of seawater adjacent to the outlets. These six regional basins listed from west to east are: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS). Although the headwaters of the Yukon and Nelson

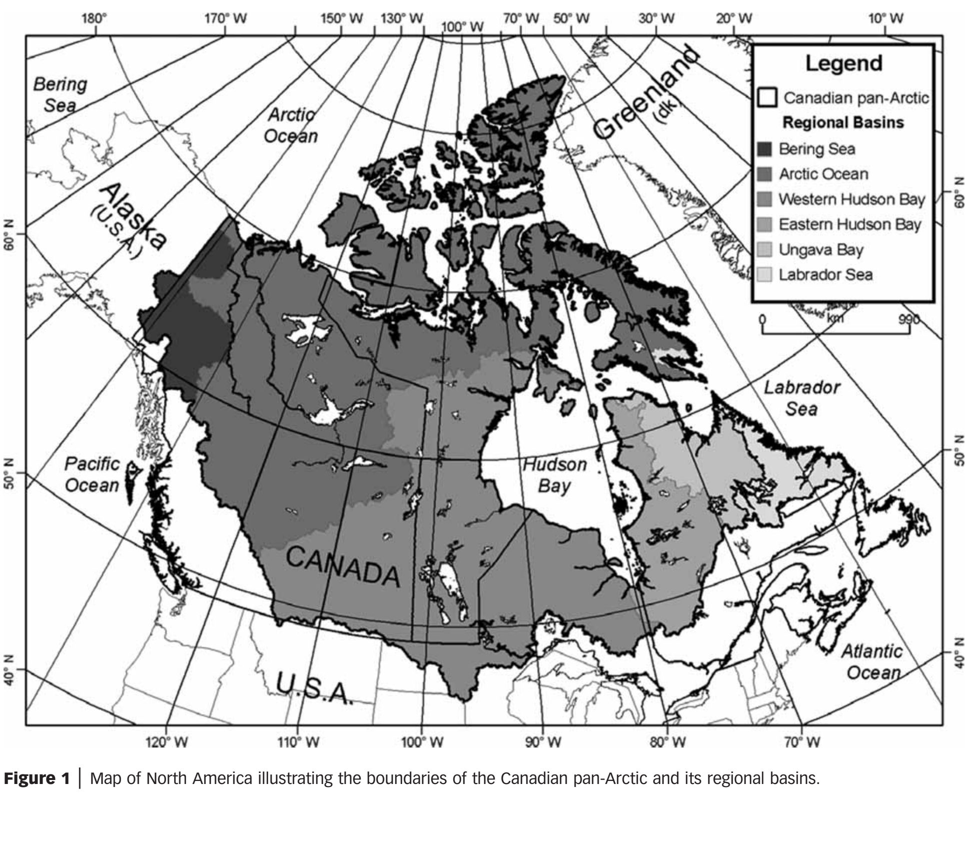

Figure 1 | Map of North America illustrating the boundaries of the Canadian pan-Arctic and its regional basins.

River systems (defined here as a river's main stem in addition to its tributaries) lie within the United States of America, they are included in the study area. Major dams emplaced along the Nelson, La Grande, Churchill (Labrador), Mackenzie, and Moose river systems further affect the seasonal flows, whereas flows from the Koksoak, Churchill (Manitoba), Eastmain, and Opinaca rivers have been partially diverted to enhance the hydroelectric power generating potential of nearby rivers (Prinsenberg 1980; Messier *et al*. 1986; Vörösmarty & Sahagian 2000).

METHODOLOGY

The river systems selected for this study are specifically chosen to maximize monitoring area for the longest period of time. Therefore ideal hydrometric gauges are located as close as possible to the sea (i.e. within Canada) and have continuous measurements from 1950 to 2008. Only one gauge on the Yukon River meets this ideal criterion. For gauges that do not have continuous measurements available for a period of record, the neighboring upstream gauge is used. At times when there are no upstream gauges (i.e. anywhere on the river), then non-existent data measurements are not in-filled. We focus on 76 rivers systems within the Canadian pan-Arctic and use between 1 and 9 gauges on each river (see Appendix, available online at http://www.iwaponline.com/nh/042/105.pdf). The 59-year study period (1950–2008) is selected because data availability becomes sparse and quality becomes questionable in northern regions prior to 1950.

The majority of the hydrometric data (1950–2008) are extracted (when and where available) from the Water Survey of Canada's (WSC) HYDAT (available online at http://www.wsc.ec.gc.ca/). Recent hydrometric data (2001–2008) for rivers in Nunavik (northern Québec) are provided by the Ministère de l'Environnement du Québec (available online at http://www.cehq.gouv.qc.ca/). The 1980–2008 hydrometric data for the intensively dammed La Grande Rivière are supplied by the power generation company, Hydro-Québec. The Yukon River station at Eagle Creek is an international gauging station (Canada: 09ED001, United States: 15356000) for which hydrometric data are provided by the United States Geological Survey (USGS; available online at http://waterdata.usgs.gov/nwis). Regardless of their origin, all hydrometric records are extracted at a daily time scale. Published data from these sources include possible cautionary flags identifying backwater or estimated flow conditions; however, such notations are ignored in the analyses for lack of better alternatives.

For compiling hydrometric time series, the total mean gauged area (A_t) for watersheds and regional basins is calculated. We first examine the hydrological record of the gauge furthest downstream for a given year. If the gauge has a complete hydrological record (as shown in Figure 2(a)) or if there is no other gauge further upstream (as shown in Figure 2(b)) we use the following formula:

$$A_t = \frac{t_D A_D}{D} \quad (1)$$

where t_D denotes the number of days the downstream gauge is active for that given year, A_D is the active area for the most downstream gauge, and D is the total number of days for that year (i.e. 365 or 366 for a leap year).

For watersheds that have multiple gauges with incomplete hydrometric records (as shown in Figure 2(c)), we again calculate the number of active days and area of the furthest downstream gauge. Similarly, we then verify the next upstream gauge and sum the number of days the

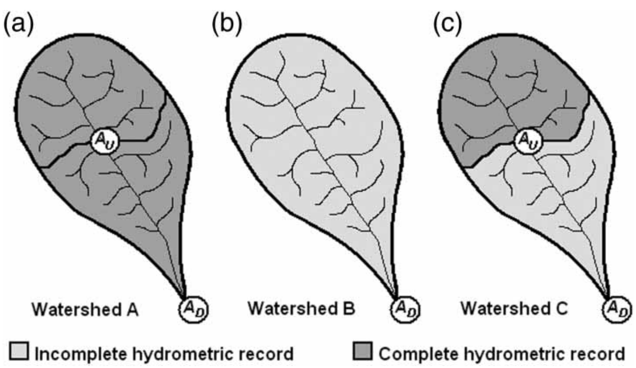

Figure 2 | Conceptual diagram showing possible spatial configurations of hydrometric gauges in relation to watersheds on the landscape. That is, a watershed can have either: (a) a downstream gauge (A_D) with a complete hydrometric record, (b) a downstream gauge with an incomplete hydrometric record, or (c) multiple gauges where the downstream gauge has an incomplete hydrometric record and successive upstream gauges (A_U) have complete or incomplete hydrometric records. Time series calculations are dependent on gauge configuration and completeness of hydrometric records (see Methods section).

gauge is active for that year (t_U) over its active area (A_U). However, t_D and t_U are the number of non-overlapping days when data are available at the downstream and upstream gauges (i.e. $t_D + t_U \leq D$). Thus, the total gauged area for any year is given by

$$A_t = \frac{t_D A_D + t_U A_U}{D} \quad (2)$$

This process is repeated if more than two gauges with partial records are available. For a given regional basin, the overall gauged area (A_O) is the sum of all n contributing watersheds (e.g. sum of watersheds A, B, and C in Figure 2) and is given by

$$A_O = \sum_{i=1}^{n} A_{t_i} \quad (3)$$

This procedure is repeated for the years spanning 1950 to 2008, providing annual time series for the entire Canadian pan-Arctic and each regional basin. For compiling time series of total gauged discharge, the same procedure is conducted.

From the compiled annual time series, additional analyses are performed. We calculate the availability of hydrometric data for each river system by spatially and temporally weighing the time series data for the period 1950–2008. For instance, if 50% of the area for a given watershed is monitored from 1951 to 1979, followed by 100% of the area being monitored from 1980 to 2008, then the overall data availability is calculated as 75% throughout 1951–2008. We then perform correlation analyses (considered significant when $p < 0.05$) between river system area and the availability of hydrometric records. To examine the temporal quality of hydrometric records (referred to hereafter as *continuity*), we sum the number of river systems with time series that have less than 10% of the data missing over a period of 30 years. The continuity analyses are carried out using 30-year moving windows, with the last year of the records ranging from 1979 to 2008. To explore the influence of dams, diversions, and reservoirs (referred to hereafter as *regulated* rivers) on streamflow, we compute time series for gauged area and discharge for known regulated rivers and 'natural' rivers.

RESULTS

The mean gauged area, relative gauged area, gauged discharge, and runoff for each of the regional basins are listed in Table 1. This table shows the number of river systems within each regional basin, as well as the area of each regional basin. Figure 3 presents the percentages of gauged areas, in relation to the regional basins. This figure highlights the amount of monitoring achieved in each regional basin as well as the variability in monitoring throughout the period 1950–2008. Regionally, the Bering Sea basin is monitored relatively more than any other basin with a minimum of 78% throughout the study period. From 1950 to 1975 the gauged area for the Arctic Ocean basin slowly increases to 50% before it plateaus

Table 1 | Summary of regional basin characteristics in the Canadian pan-Arctic (CP-A). Averages are computed for the entire study period (1950–2008) and the number of river systems in each regional basin is in parentheses. The six regional basins are listed from west to east: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS)

	Regional basin		Mean			
		10^6 km^2	Gauged area 10^6 km^2	Relative gauged area %	Gauged discharge km^3 yr^{-1}	Runoff mm yr^{-1}
(2)	BS	0.36	0.34	94	84	248
(16)	AO	3.88	1.66	43	321	193
(24)	WHB	2.75	1.86	68	264	142
(18)	EHB	0.57	0.26	46	187	714
(9)	UB	0.38	0.15	39	75	505
(7)	LS	0.29	0.11	37	67	628
(76)	CP-A	8.23	4.37	53	998	228

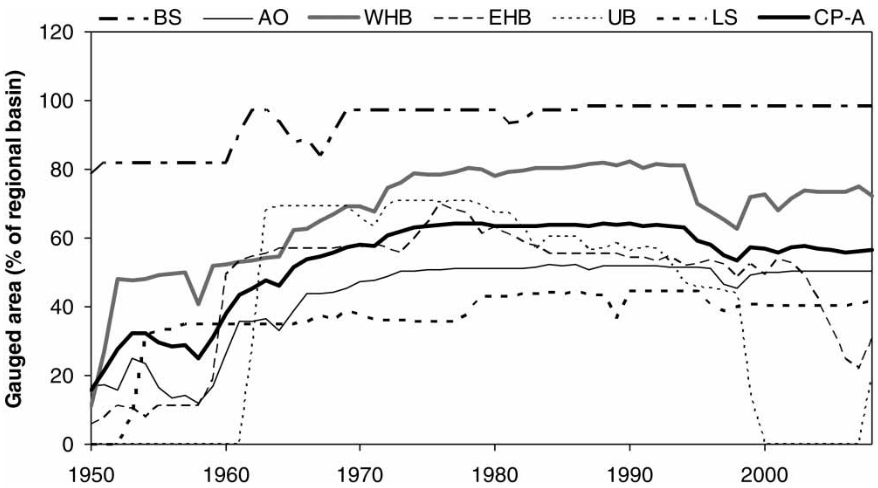

Figure 3 | Relative percentage of gauged area for the Canadian pan-Arctic (CP-A) and each regional basin throughout the period 1950–2008. The six regional basins are: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS).

from then on. The gauged area in the Western Hudson Bay basin increases steadily from 1950 to 1977, but remains steady at about 79% afterwards. The Eastern Hudson Bay basin slowly increases from 1950 to 1976, where it reaches a maximum gauged area of 69%; however, the gauged area steadily declines thereafter until 2008. The smaller regional basins are not continuously gauged as monitoring was not established in Ungava Bay and Labrador Sea until 1962 and 1953, respectively. In subsequent years, monitoring in Ungava Bay increases to 69%; however, all monitoring was discontinued in 2000 only to be partially reinstated in 2008. In the Labrador Sea basin, the gauged area slowly increases from 31% in 1953 to 41% in 2008. In 1990, the gauged area for the regional basins collectively monitored 64% of the Canadian pan-Arctic. The evolution of the gauged area for the Canadian pan-Arctic closely mimics that of the Arctic Ocean and Western Hudson Bay basins as a result of their large contributing areas.

The relative contributions of each regional basin and the absolute gauged area for the Canadian pan-Arctic are shown

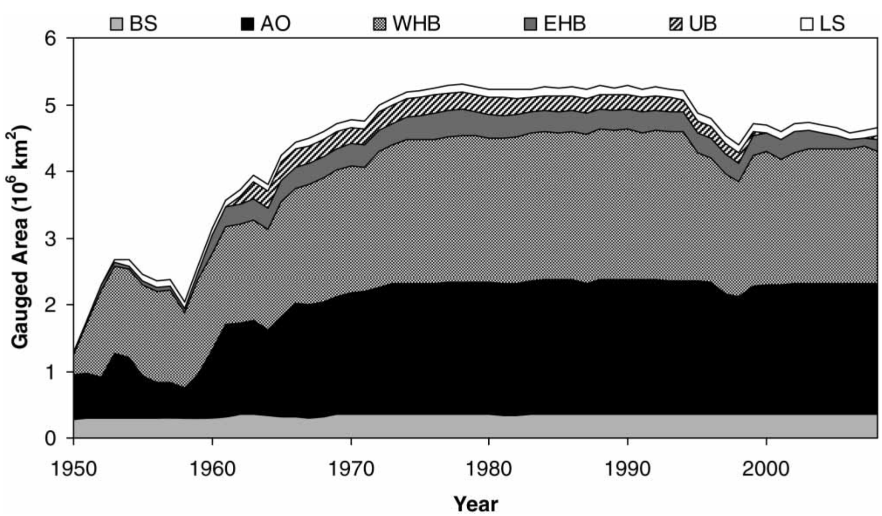

Figure 4 | The total annual gauged area for the Canadian pan-Arctic throughout the period 1950–2008. The time series shows the relative gauged area contribution for each regional basin are: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS).

in Figure 4. This highlights that the Arctic Ocean and Western Hudson Bay basins have the largest gauged areas attributed to the Mackenzie and Nelson river systems. Together the remaining regional basins account on average for less than 20% of the total gauged area of the Canadian pan-Arctic.

When gauged area (Figure 4) is compared with gauged discharge (Figure 5), two points become evident: (1) discharge quantity is not dependent on area; and (2) discharge varies from year to year. For instance, the four smallest regional basins (20% of total gauged area) collectively contribute to 41% of the total monitored discharge. This is a result of regional patterns in the hydrological cycle as demonstrated by the runoff rates calculated for each regional basin, which are listed in Table 1.

The percentage of data availability for each river system is shown in Figure 6. It is apparent that there is a large range in the variability of record availability. The Yukon River is

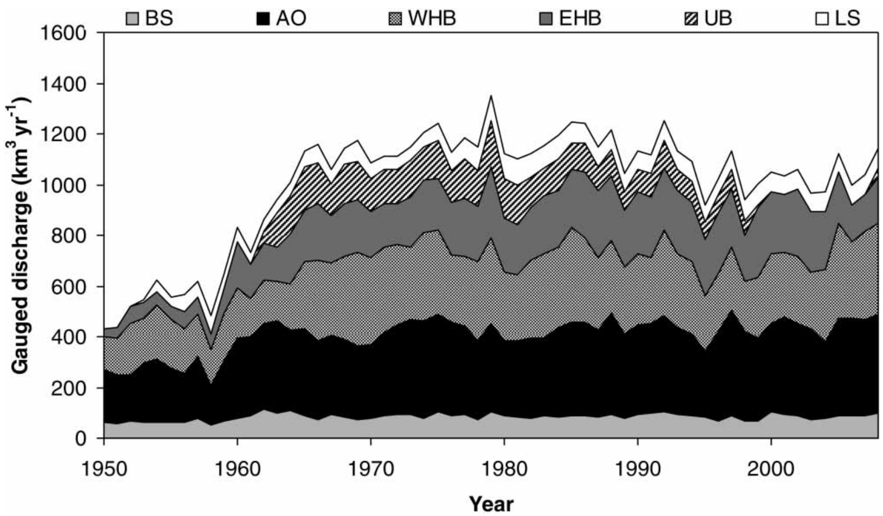

Figure 5 | The total annual gauged discharge for the Canadian pan-Arctic throughout the study period 1950–2008. The time series shows the relative discharge contribution for each regional basin are: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS).

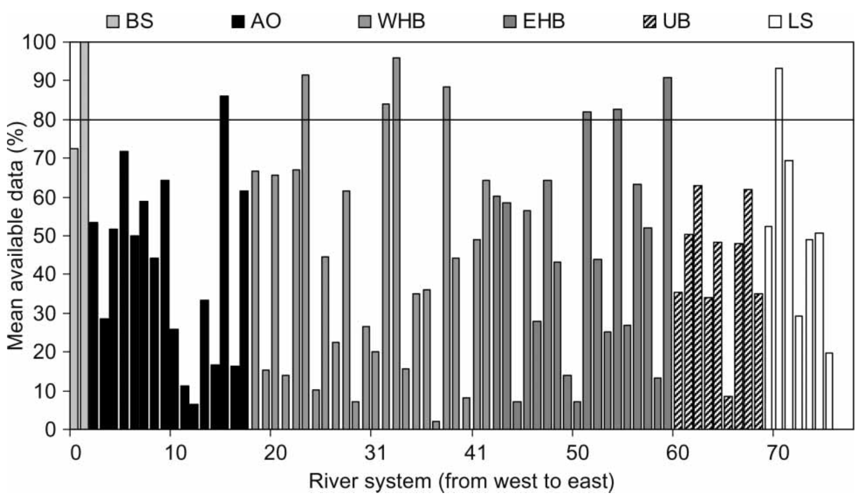

Figure 6 | Spatially- and temporally-weighted percentages of available hydrometric data for each river system within the Canadian pan-Arctic, 1950–2008. The horizontal line shows the spatial and temporal average of available data for the Canadian pan-Arctic. The six regional basins are: (1) the Bering Sea (BS), (2) Arctic Ocean (AO), (3) Western Hudson Bay (WHB), (4) Eastern Hudson Bay (EHB), (5) Ungava Bay (UB), and (6) the Labrador Sea (LS).

the only river system with a complete hydrometric record for the entire study period, whereas the Saqvaqjuac River only has 2% of its hydrometric records available. With spatial and temporal averages considered, the 76 river systems within the Canadian pan-Arctic have 80% of the hydrometric records available. Without spatial and temporal averages considered, each river system has an average of 46% of the data available throughout the study period. There was no relationship between spatial distribution and the availability of hydrometric records. However, Figure 7 shows a significant positive correlation ($r^2 = 0.51$, $p < 0.01$) between river system area and availability of hydrometric records, implying that larger rivers are likely to have more complete hydrometric records.

Figure 8 shows the continuity of hydrometric time series for the Canadian pan-Arctic. Here hydrometric time series must have less than 10% of the data missing over a period of 30 years to be considered as continuous. If this criterion

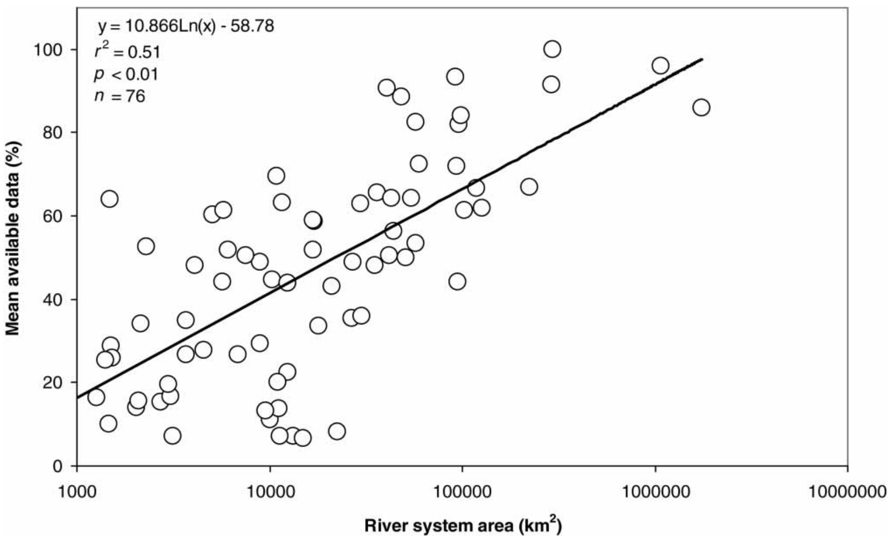

Figure 7 | Relationship between the river basin area and availability of hydrometric records for the period 1950–2008. The black line is the linear regression.

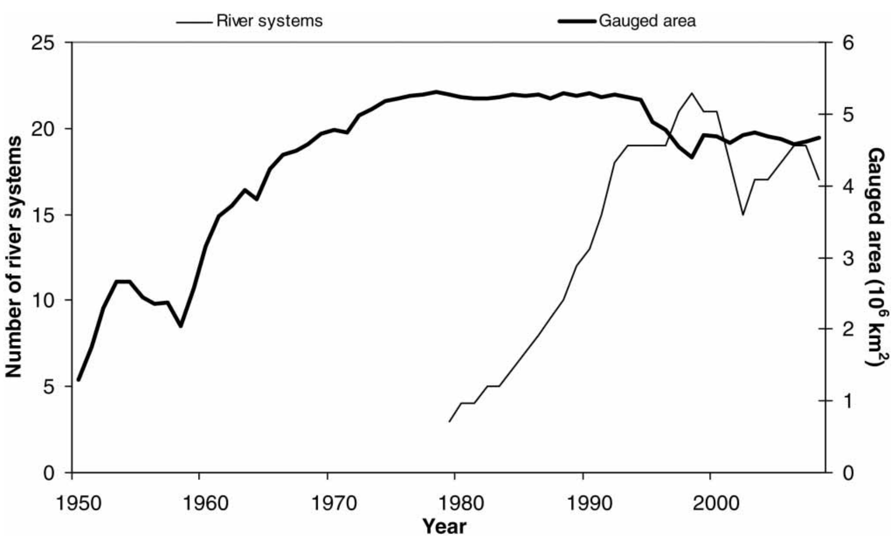

Figure 8 | Time series showing the number of river systems with no more than 10% missing data for periods of 30 years. Total gauged area for the Canadian pan-Arctic is shown as a reference.

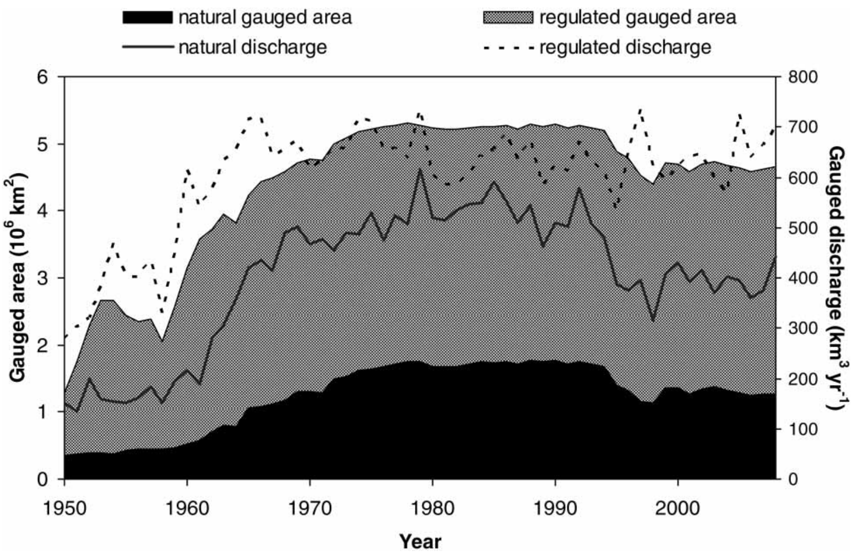

Figure 9 | Temporal evolution of total annual gauged area and discharge for 'natural' and 'regulated' river systems in the Canadian pan-Arctic, 1950–2008.

is met, the maximum possible number of time series can be as much as 76 with the earliest possible year commencing in 1979 (referenced for the last year of the 30-year period). A maximum of 22 river systems in 1998 attained this criterion. From 1992 to 2008, 15 river systems maintained a continuous 30-year record without being discontinued or experiencing any major data gaps. A final analysis examines the general proportion of gauged area and discharge values for regulated rivers compared to those of natural rivers (Figure 9). This illustrates that the majority of discharge (≈52–75%) and gauged area (≈66–86%) in northern Canada is affected by water regulation throughout the entire study period.

DISCUSSION

This study focuses on how well Canada is monitoring river discharge to high-latitude oceans. Based on the 76 rivers included in this study, the maximum gauged area for the Canadian pan-Arctic reached 64% in 1990, but has since declined to 56% as of 2008. This negative trend accords well with the findings of previous studies (Lanfear & Hirsch 1999; Shiklomanov *et al*. 2002) that investigate the management of hydrometric networks in the pan-Arctic region and United States. Due to government budget reductions in 1995, monitoring programs across Canada were forced to discontinue hydrometric stations (Pilon *et al*. 1996). Within the Canadian pan-Arctic, monitoring is variable throughout the regional basins as well as throughout the study period. It is likely that much of this variability can be attributed to many challenges faced by management organizations. For instance, Ontario's hydrometric network in the 1990s faced many challenges (that contributed to gauge deactivation) that include: (1) rising costs and reduction in funding, (2) changing ownership of data, (3) cost recovery, (4) change from central agency to multiple agencies for the collection and dissemination of data, resulting in fragmentation and duplication, (5) rapidly changing technology, (6) increased data needs, (7) climate change, and (8) the need to define a basic provincial network and establish a priority of stations (Dillon Consulting Limited 1996). Furthermore, geographical attributes allow some regional basins to be monitored more easily than others. For example, it takes two gauges to monitor all of the discharge flowing into the Bering Sea, but for a similar sized area such as Ungava Bay, it takes nine gauges to monitor up to 71% of the regional basin.

The World Meteorological Organization (WMO 2009) states that 'it is important to have a desirable future for which to aim and then use integrated water resources management as means to achieve it'. If at all possible, 100% of the Canadian pan-Arctic should be monitored, but given the large area, remoteness, and harsh environmental conditions, attaining this goal is neither likely nor possible. If 50% of the gauged area is to be the acceptable threshold, then the Canadian pan-Arctic is already sufficiently monitored. An effective gauged area should be sought after, but what would be an effective gauged area? For the purpose of this study, we choose 75% as an acceptable threshold for an effective gauged area. This figure is selected here so that a majority of the area in the six regional drainage basins is actively monitored in any given year, reducing the uncertainties in total (gauged + ungauged) estimates of river discharge to polar seas. This is a reasonable assumption as river runoff rates do not fluctuate substantially along the northern perimeter of the Canadian pan-Arctic and can therefore be inferred using nearby hydrometric data (Déry *et al.* 2005; Spence & Burke 2008; Hernández-Henríquez *et al.* 2010). Following Mishra & Coulibaly (2009, 2010) and others, future work will focus on analyzing in detail what is a sufficient monitoring threshold to obtain accurate estimates of total river discharge in northern Canada.

Our results demonstrate that the Canadian pan-Arctic and most regional basins can be improved to meet the monitoring goal of 75% spatial coverage. Currently, the Canadian pan-Arctic would need to increase its gauged area by a total of 1.5×10^6 km^2, or roughly the same size as the province of Québec. This area can be decreased to 0.68×10^6 km^2 if all 76 river systems in this study were completely monitored. If this were to happen, the Eastern Hudson Bay and Ungava Bay basins would approach the threshold goal with 72% and 71%, respectively. The Arctic Ocean and Labrador Sea basins, however, only increase their gauged area to cover 53 and 44% of the regional basins, respectively. According to the WSC, the ungauged areas within these four regions have never had many hydrometric stations with none having long continuous records. Presumably, the remoteness and harsh conditions increase the cost of establishing and maintaining any gauges in these regions. Furthermore, the ungauged regions are reduced to smaller river systems where it would require many gauges to cover a large area. For instance, if the average ungauged river system had an area of 10,000 km^2, then an additional 68 hydrometric gauges would be needed to increase the total gauged area in the Canadian pan-Arctic to 75%. The addition of 68 stations to the Canadian hydrometric network (currently consisting of ≈2800 stations) would not make a large impact; however, 68 stations in northern regions would make a substantial difference.

Within the Canadian pan-Arctic, the Arctic Archipelago has the greatest potential to increase its gauged area as less than 1% is currently gauged (Déry & Wood 2005; Spence & Burke 2008). The archipelago receives little precipitation annually (Goodison 1978) and rivers are likely to ice over or dry up for a portion of the year. Furthermore, any additional station would likely be expensive to deploy and maintain. For these reasons, the archipelago is not an ideal location for additional gauges in spite of the tremendous need for hydrological information there. Alternatively, the Eastern Hudson Bay, Ungava Bay, and Labrador Sea basins might be more suitable because of their relatively high runoff rates (see Table 1).

When considering spatial and temporal availability of data for the 76 river systems, a large percentage (80%) of the landscape has hydrometric data. This is a relatively high percentage when 66 of the 76 river systems do not have such coverage. Of the 76 river systems, the average river has 46% of its hydrometric data available for the entire study period. Inadequate data availability in many regions can be explained by poor monitoring from 1950 to 1970, especially for many of the smaller river systems. There is no regional pattern for data availability; however, the significant correlation between river system areas and available hydrometric data suggests that river system size is of primary importance in the establishment and maintenance of hydrometric monitoring stations in northern Canada. That is, if a gauge has to be discontinued, it is more likely to be on a smaller river system. This prioritization is understandable when management has financial restrictions. Nonetheless, the value of hydrometric data for small rivers cannot be stressed enough, especially when quantifying discharge entering the oceans. In addition, Canada will need to start surveying more small rivers in the future if 75% of the Canadian pan-Arctic is ever to be monitored.

It is recommended that climate averages should have continuous records lasting a minimum of 30 years (Barry & Chorley 1987). Similarly, hydrometric stations with long term records (i.e. ≥30 years) are of significant value when computing long-term flow characteristics (Lanfear & Hirsch 1999). Out of 76 river systems used in this study, only 22 river systems for any single year had a continuous record of 30 years. Since 1992, only 15 rivers systems managed to maintain a 30-year continuous record without being discontinued or experiencing any major data gaps. With few rivers meeting this standard, it becomes difficult to accurately relate streamflow variability and trends to climate in the pan-Arctic.

It is important to note that a large portion of the discharge reaching the oceans is regulated (as opposed to natural). During the mid-1990s, when the total gauged area was declining, the discharge for regulated rivers remained relatively stable whereas discharge for natural rivers continued to decline. This suggests that monitoring of regulated rivers is more stable than that of natural rivers as a result of long-term infrastructure in place for economic development. The regulation of rivers, similarly to data availability and continuity of hydrometric records, can affect the quality of hydrometric data as well as add complexity to any analysis. The combination of poor data availability and the development of flow regulating structures on rivers in northern Canada can negatively affect studies investigating the changing environment in the north. This is especially disconcerting since the Arctic region is an area where significant climate change is occurring (Serreze *et al*. 2000).

CONCLUSION

For our evaluation of hydrometric monitoring in the Canadian pan-Arctic, we quantify monitoring by compiling time series of available hydrometric data corresponding to the total gauged area and discharge. Based on gauged area, hydrometric monitoring initially experiences a rapid increase in the 1950s and 1960s before levelling off in the 1970s and 1980s. In 1990, the maximum gauged area (64%) of the Canadian pan-Arctic is attained, but the total gauged area gradually decreases to 56% by 2008. Our results further suggest that monitoring quality has to be improved with regards to the continuity of hydrometric records and the availability of data for river systems. That is, there are few rivers that have more than 30 years of continuous records, which becomes problematic when studying long-term changes in the environment and climate. Also, data availability tends to be better for large rivers, whereas data availability tends to be poorer on the small rivers in the more remote regions. In the future, if more of the Canadian pan-Arctic is to be monitored, additional gauges on relatively smaller rivers will have to be deployed. Although new gauges could be deployed in the Arctic Archipelago, new gauges will be the most efficient at monitoring discharge in the Eastern Hudson Bay, Ungava Bay and Labrador Sea basins.

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