Queen Elizabeth Islands: problems associated with water balance research

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Abstract  The Queen Elizabeth Islands in Arctic Canada are in an extremely remote region with long, cold winters, and 2- to 3-month summers, with 24-h daylight. Snow is a major part of annual precipitation, but there are few Arctic weather stations and precipitation data accuracy is hampered by gauge undercatch. Large spatial variations in snowmelt and evaporation make it difficult to extend point calculations over a basin. Currently no official hydrometric station exists in the Islands and the short-term available records are afflicted by stream gauging problems during peak flows. Annual water balances are often not closed, as not all the components are measured or calculated; this applies to early studies and to all glacierized catchments. Given the sensitivity of polar regions to climatic change and the likely importance of freshwater input to the Arctic Ocean, performing proper water balances for the basins in the Arctic Archipelago is a challenge.

Key words  Canadian Arctic; evaporation; permafrost; precipitation; Queen Elizabeth Islands; runoff; storage; water balance

INTRODUCTION

In the early 1970s, interest in Arctic hydrological research was largely stimulated by the planning of megaprojects in the Canadian Arctic Islands, such as the opening of mines and the designing of gas pipelines. An assessment of the various hydrological quantities was fundamental to rational water use planning and prevention of water-related hazards (e.g. pipeline and road construction through ecologically sensitive areas, including wetlands and wildlife habitats). Today, northern development is still important (e.g. mining and renewed prospects for oil and gas exploration) but recent hydrological research is also driven by the need to assess the impacts of climatic change and variability on Arctic water resources (Young & Woo, 2003). Climate change scenarios suggest that Arctic environments will face dramatic shifts in both temperature and precipitation, which can alter the runoff regime and evaporation rate, accompanied by permafrost thawing and ecosystem adaptation. Improved understanding of the amounts, distribution, and timing of runoff from the land, both on large and small scales, is of interest to oceanographers since freshwater input may influence the thermohaline circulation of the Arctic Ocean (Hakkinen et al., 2004).

One unifying characterization of the hydrological processes in a geographical region is its water balance, which evaluates for a given period the amount of water gained, lost and stored in a defined catchment:

\[ S_n + R - E - Q = \frac{dS}{dt} \]  \hspace{1cm} (1)
where $P = (S_e + R)$ is precipitation input of snowfall ($S_e$) and rainfall ($R$), $E$ is evaporation, which includes transpiration, $Q$ is runoff and $dS/dt$ is change in storage (e.g. ground ice melt, glacier ice ablation, depression storage). The snow will eventually melt, sublimate, or it may enter storage. Previous assessments of water balance in the Arctic environment have raised issues regarding the evaluation of water balance quantities. The difficulties of obtaining data and the errors of measurement and calculations are particularly serious for the polar locales. The water balance of river basins in the Queen Elizabeth Islands, Arctic Canada, has been inadequately covered and suffers from all the logistical problems associated with field investigation in the extreme North. This study systematically examines the challenges of obtaining water balance estimates for remote cold regions. Information provided in this paper sets the background against which the accuracy of water balance research in the far North can be appraised.

PHYSICAL SETTING

The Queen Elizabeth Islands extend north of 74°N to about 83°N, and lie between 60.5°W and 126°W (Fig. 1). The land area of the Archipelago is about equal to that of France, but the islands are separated by many straits and sounds that remain covered by sea ice for nine or more months each year. The eastern flank of the Archipelago has rugged topography, with mountains that often rise abruptly from sea level to over 2000 m. Many high grounds have ice caps that produce tongues of valley glaciers that sometimes reach sea level. The Arctic lowland in the central section is occupied by a dissected plateau. The western fringe is the Arctic coastal plain, a low-lying area that slopes gently northwestward toward the continental shelf.

![Queen Elizabeth Islands](image-url)
The region is characterized by continuous darkness during most of the winter months and uninterrupted daylight in the summer. In spite of the long sunshine hours in the summer, low sun angle and high reflectivity of the surfaces limit the amount of radiation received. In winter, there is substantial heat loss from the surfaces. These conditions render the region extremely cold, favouring the development and maintenance of permafrost, which underlies all lands and reaches thicknesses of 400 m in the south to over 600 m in the north. The active layer thickness varies depending on soil and moisture conditions, but it rarely exceeds 1 m. Prolonged cold curtails vegetation growth. The area is largely barren, except at locations where local heat and moisture supplies permit tundra vegetation development. Such sparsely vegetated polar regions are referred to as the High Arctic.

The intrusion of cold Arctic Ocean air over the Sverdrup Lowlands and the sheltering effect of the mountain barriers in the east form an S-shaped temperature pattern over the region (Fig. 2). This macro- or synoptic-scale phenomenon extends to

![Fig. 2 Mean monthly summer temperature °C over the Queen Elizabeth Islands for (a) June and (b) July (after Alt & Maxwell, 2000).](image-url)
about 1 km in the atmosphere and reflects the impact of regional topography on the troposphere (Alt & Maxwell, 2000). The pattern is pronounced in the summer months (Edlund & Alt, 1989). Inland locations, particularly the intermontane sites, tend to be warmer than the coasts in the summer. Field results from Ellesmere Island demonstrate that the inland site of Hot Weather Creek, 25 km from the coast, had July mean temperatures that were 2–5°C warmer than Eureka at the coast. The difference was larger in the warm summer of 1988 than in the cold, wet summer of 1989 (Edlund et al., 1990).

The major controls of precipitation are the frequency and intensity of cyclonic activities, with secondary factors being the interaction of topography and mean atmospheric conditions. Warm advection (warm air streams) accompanying travelling cyclones bring in much of the moisture to the Arctic Islands. High grounds and exposed windward slopes enhance precipitation through orography. The eastern coasts of Baffin and Devon islands receive high precipitation under the influence of the open water between Greenland and the Canadian Arctic Islands. A secondary high precipitation zone lies on the windward (western) side of the mountain barriers on Ellesmere and Axel Heiberg Islands. Precipitation minima are found in areas that experience the precipitation-shadow effect, such as the Eureka Sound intermontane region, or in the western islands that are subject to the persistent influence of surface anticyclones (Alt & Maxwell, 2000). Snow may fall during any month of the year and the snow cover, once established in September, will last for nine to ten months.

Owing to the coldness and low precipitation, the Queen Elizabeth Islands are considered to be a polar desert largely barren of vegetation. The exceptions are the polar oases where tundra vegetation growth is relatively luxuriant. Woo & Young (1997) noted that the oasis around Eureka is warmer, but drier, than the polar desert of Resolute, suggesting that it is heat rather than moisture that is the prime factor limiting plant growth in the region. For the Arctic Archipelago, Edlund & Alt (1989) showed that the northern limit of woody plants and sedges correspond roughly with the mean July isotherm of 3° and 4°C, respectively.

PROBLEMS OF MEASUREMENT

Shiklomanov et al. (2002) noted that there is a drastic decline in the hydrometric network in the Pan-Arctic region. The Queen Elizabeth Islands are no exception. The loss of long term monitoring stations at the end of the last century leaves an enormous void in this region. Water balance investigations, already difficult in this remote High Arctic, will be furthered hampered in the future.

Precipitation

Snowfall and rainfall are routinely measured at the official weather stations operated by the Meteorological Service of Canada (MSC). All MSC weather stations are located near sea level, with no data for the inland and high elevation sites. Even the sparse coastal data collection network has undergone attrition, leaving only three monitoring stations for the entire Queen Elizabeth Islands. While automatic weather stations are set up, their precipitation data are of questionable quality, particularly in the winter,
due to riming on the instruments and infrequent maintenance. Errors in the data cannot be easily isolated and rectified.

Snowfall is often the major component of precipitation, but its measurement suffers from inaccuracies due to poor gauge catch under windy conditions (Yang et al., 2001). In Canada, the nipher shield is used for all official gauges to enhance gauge catch (Fig. 3) but there are still underestimations due to the sublimation of light snow falling on the gauge rim or the accumulation of snow arching over the gauge opening without dropping into it. Woo et al. (1983a), for example, found that total snowfall recorded at the weather stations represented only 40–60% of the total winter accumulation in their nearby basins. The underestimation of precipitation is further evidenced by a comparison of the official precipitation map, interpolated from limited coastal weather station records (Maxwell, 1980), with the map produced by Koerner (1979) using snow accumulation measured on ice caps (Fig. 4). There are recent attempts to correct the station snowfall records and to adjust coastal station data to reflect the conditions at interior sites through an end-of-winter snow cover index approach (Yang & Woo, 1999). Here, snow information obtained for interior terrain (valleys, uplands and slopes of different aspects) is compared to the weather station value to develop ratios or indices with which future station snow data can be extrapolated to interior sites. This approach appears to be suitable for rolling topography (Woo & Young, 2004) but cannot be applied easily to steep mountainous locations (Hardy, 1996; Ohmura, 1982a) where extensive snow measurements cannot be made to derive the indices.

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Fig. 3 A nipher-shielded precipitation gauge with its funnel shaped orifice, Resolute, Cornwallis Island.
Like snowfall, rainfall may be underestimated as gauge catch efficiency decreases with wind speed. Light drizzle and fog produce events that are recorded as trace rainfall which are frequent in the region, particularly along the coast when the sea ice has melted. Goodison et al. (1993) recommend that non-zero values be given to such events that cannot be measured by conventional methods. Woo & Steer (1979), using

Fig. 4 Comparison of mean annual precipitation: (a) interpolated using 30 years of record from six coastal weather stations, after Maxwell, and (b) using snow pit data from snow profiles on ice caps, according to Koerner, for the period August 1962 to August 1973.
absorbent paper to catch such trace precipitation, found that its magnitude averaged 0.01 mm h$^{-1}$. When applied to the many trace events recorded, the total reached 1.5 mm, a notable portion of the 9.2 mm of total rainfall for the dry summer of 1977.

The spatial distribution of rain and snow in a drainage basin can be sufficiently large to render single point measurements unrepresentative for water balance calculations. This is particularly serious for snow distribution, which is well known to be highly variable, depending on interactions between topography, wind and snow drifting. During the melt period, shallow snow quickly disappears but deep snow lingers for a long time. Without knowing where the meltwater comes from and the changing percentage of snow-covered areas in a basin, the timing and magnitude of runoff generation cannot be correctly obtained. For small basins, it is possible to model snow distribution using wind speed, direction and topographic parameters, as has been done in the Low Arctic tundra of Trail Valley (Essery et al., 1999). For medium basins, topography can provide the basis for subdividing the basins into terrain units. Then, an end-of-winter snow survey conducted for each terrain type allows for the estimation of the snow variations (Woo et al., 1983b). Over large areas, remote sensing may be required to map the snow distribution. However, its application remains limited by algorithm development, lack of validation, and long return times of the satellites. To date, RADARSAT can only map shallow snow cover (Rubinstein, personal communication), and passive microwave information can be used only for conditions of low snow water equivalent.

Underestimations in weather station precipitation records have caused water balances to produce erroneous results, yielding insufficient precipitation to account for annual evaporation and runoff losses. Substituting the total snowfall record by end-of-winter snow cover measured on the ground has improved basin water balance calculations (Woo, 2000). The quality of precipitation data has tremendous implications for water balance investigations, because it is the ultimate or immediate water source that drives the water balance. Errors in precipitation measurement, often considerable in the High Arctic due to strong winds and fog, make it extremely difficult to close the water balance for drainage basins. Furthermore, few gauges are available in most studies to capture the spatial distribution pattern of precipitation. Improvements are needed to obtain accurate snow data and to depict the spatial variations of snow accumulation and rainfall.

Evaporation

Defining the magnitude of over-winter sublimation of blowing snow is one of our present challenges. Recent development of blowing snow models in Canada has not produced agreement on the most appropriate approach to calculate sublimation losses. The Prairie Blowing Snow Model (Pomeroy et al., 1993) yields sublimation rates that are at least an order of magnitude larger than the PIEKTUK model (Yau & Déry, 2001). Using an energy balance approach, some studies have indicated that sublimation is significant at polar oases sites such as Truelove Lowland (Rydén, 1977), western Axel Heiberg Island (Ohmura 1982b), or Hot Weather Creek (Woo & Young, 1997). The values have not been verified by direct measurements of snow loss during the time that they are actually occurring.
As the melt period progresses, the snow cover becomes fragmented while meltwater runoff is blocked by uneven snow distribution in the stream valleys. Integrated channel network is established only after the snow dams are breached, and this invariably delays streamflow response to snowmelt. (Photo of McMaster River basin, Resolute.)

While estimates of sublimation are prone to error, evaporation calculations can be problematic. Evaporation is usually determined for single sites and the computed values are extrapolated to the entire basin. This approach is notably invalid during the snowmelt season when the snow cover is fragmented into patches (Fig. 5). Snowmelt on snow patches (Neumann & Marsh, 1998) and evaporation from the snow-free zone occur simultaneously, with heat advection and large variations in moisture availability in the basin causing great difficulties in extending point estimates of evaporation and melt rates over an area.

Several approaches have been employed to obtain evaporation estimates in High Arctic basins. Direct measurements using small lysimeters have been made, but they suffer from lack of representativeness as the soil inside the lysimeter may dry out differently from the undisturbed site, and there is no lateral or vertical moisture exchange with the surrounding soil. Computation methods have been used, including the Bowen ratio method (Ohmura, 1982b), Penman-Monteith method (Young & Woo, 1997), and the Priestley and Taylor approach, with its V-coefficient related empirically to the surface soil moisture (Marsh et al., 1981). While these approaches require different sets of measurements (e.g. net radiation, temperatures, vapour pressure and/or wind speed), all field studies are limited to single sites. For basin studies, questions
related to the extension of point observations over surfaces with different cover and terrain conditions need to be considered.

It is further noted that in some early studies, evaporation was assumed to be insignificant in some environments (e.g. glacierized basins) and therefore was eliminated in the water balance estimates. Alternately, evaporation was obtained as a residual term in the water balance, which is problematic since errors in the other terms in equation (1) are all incorporated in the evaporation estimate.

Streamflow

The flow of rivers in the temperate or tropical latitudes can often be obtained easily at the basin outlets by establishing stage–discharge rating curves and by applying these curves to the river stage monitored continuously by water level recording devices. Unless the gauging stations are located at stable channels such as narrow gorges, the rating curves for most High Arctic rivers tend to change over a season as the streams wander and the channels shift. The situation is especially complicated in the initial flow period when channels are being established in the snow-filled valleys. In the Queen Elizabeth Islands, the lack of winter flows prevents the formation of ice in the channel, a condition that contrasts sharply with the massive river ice cover in Low Arctic and subarctic streams. Snow infills the dry valleys and drifting reshapes the snow mass into ridges and troughs which, during the initial runoff period, become dams and pools as meltwater enters the valleys. Until the snow dams are breached (Xia & Woo, 1992) there is no integrated flow but once the flow network is established, the stream has to cut vertically and laterally through the residual valley snow (Fig. 5). During this period, there is no stable stage–discharge relationship for most sites and direct discharge measurements have to be made. Stream gauging under such conditions is extremely hazardous because of the fast flows and the slippery snow and ice underfoot. Yet, this is the time of peak flows and much of the annual discharge may have already been released before the channel is stabilized. At least two discharge measurements have to be made each day to capture the high and low values in order to estimate the diurnal flow rhythm. Even so, the errors may be substantial.

Although the summer channels are relatively stable, many pro-glacial sandar or periglacial sandar have shifting channels (Vandenberghe & Woo, 2002). This may require adjustment of the stage–discharge rating curve, or even a change in the location of the stilling wells.

Change in storage

In this continuous permafrost region, groundwater storage is small due to the thin thawing of the active layer that refreezes completely in winter. There can be year-to-year change in ground ice storage, as well as some degradation of the permafrost after an exceptionally warm summer, and frost aggradation in a cold, wet summer (Edlund et al., 1990). These processes cause a change in storage, but the magnitude is small relative to the other terms of the water balance. On the other hand, annual storage
change due to increase or depletion of semi-permanent snowpacks that lie on slope concavities or in shaded valleys can be significant, as can lake storage changes. Some early studies assume that the annual change in storage approaches zero, but this is unlikely to be true. It is exceedingly difficult to directly measure all the storages in the basin so that the storage change term is treated as a residual in the water balance calculations.

Glacierized basins

Parts of eastern and northern Queen Elizabeth Islands are clad by glaciers. The delineation of drainage divides on the ice caps can only be approximated, and this is a major source of inaccuracy in water balance evaluation. Large elevation range and rugged topography cause considerable spatial variations in precipitation, ablation, evaporation and storage change, but accessibility often restricts the measurements to the lower parts of the basins. The accumulation and ablation of mass on high altitudes have been measured annually at limited locations (Koerner, 1970) but these results have not been linked to basin water balance studies that involve both the glacier-covered and the ice-free zones. Thus, despite the possibly ample contribution of freshwater from glacierized basins to the polar seas, their water balance remains insufficiently investigated.

DISCUSSION AND CONCLUSION

Hydrological research in the past decades has greatly improved our understanding of the processes that influence water balance, and we have obtained useful information regarding the gains and losses of water at different times of the year for many typical hydrological regimes. Most works were carried out in the barren polar desert or tundra-covered polar oases environments. The water balance of glacierized basins and basins dominated by lakes and wetlands remains insufficiently studied. Geographically, past studies were restricted mostly to a north–south transect along the central corridor (see the accompanying paper), with no water balance investigation for most of the eastern mountains and none in the western islands.

Water balance investigations demand fundamental measurements of precipitation and streamflow, with climatic and hydrometric stations providing the requisite data. This paper has presented the difficulties of obtaining accurate measurements of precipitation and streamflow in the cold environment, and the logistical problems that often prevent acquisition of sufficient spatial coverage of the water balance components. It is important to note that most of the water balance results quoted do not quantify the uncertainties of the components or measurements, making it almost impossible to evaluate the errors arising from the water budget assessment. Only snow survey results from Woo & Marsh (1977) were reported to have an error of about 15%, while the errors for other components of the water balance remain unknown.

The recent trend of data collection is most discouraging. All stream gauging stations have now been eliminated from the Queen Elizabeth Islands and there is a
continued attrition of the already sparse climatic data monitoring network. The task of obtaining data for water balance studies falls largely on university field parties that unfortunately have to curtail their field work to fit other summer academic duties. This sometimes leads to an incomplete seasonal coverage of various water balance components of the hydrological cycle, particularly during the early flow or the freeze-back periods.

Energy and water balances are strongly linked in the High Arctic due to freeze-thaw, evaporation and sublimation processes, snow-ice albedo feedback, and moisture control on the partitioning of latent and sensible heat fluxes. With projected climatic warming due to anthropogenic influences, there may be large-scale changes in the energy and water balances, leading to such effects as permafrost degradation; enhanced glacier ablation at low elevations; lake and wetland alteration; and shifts in the snowmelt, evaporation and runoff regimes. There may also be an increase in precipitation in the high latitudes that may lead to larger river discharge, which influences oceanic circulation patterns (Rahmstorf, 1996; Hakkinen et al., 2004). On a shorter time scale, variability in the climate affects the year-to-year variations in basin water balance as well as the frequency and magnitude of extreme events (Cogley & McCann, 1976; Woo, 2003). These long-term changes and short-term variations have been captured by climatic models, but to verify the model results using measurement-based water balance evaluations remains a challenge to the hydrological community.

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