Winter streamflow as a source of uncertainty in water balance calculations

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Abstract Discharge during the season of ice-effect can be an important component of an annual water balance at high latitudes. Standard hydrometric methodology is incapable of providing reliable discharge data during the winter season, and most winter streamflow data are estimated based on a few broadly held assumptions. Examples showing conditions during which these assumptions are invalid are provided. There is currently no way to estimate the uncertainty introduced into water balance calculations by acceptance of these assumptions, so interpretation of calculated runoff volumes should reflect that unknown uncertainty, particularly for basins subject to extensive ice cover. Further research is needed to understand and develop a predictive ability for winter streamflow variability.

Key words break-up; discharge depression; freeze-up; ice effect; stage-up; water balance; winter streamflow

INTRODUCTION

Most of the quantities required for water balance calculations are difficult to measure accurately, even within the context of a research watershed. The quantity that is most likely to be accurate is runoff, because the drainage structure of the basin handles the problem of spatial integration, leaving the researcher with the relatively small problem of temporal integration of discharge. However, there can be errors in runoff estimates that may be important in seasonally ice-covered rivers.

The techniques and technologies for survey and monitoring of streamflow are robust and reliable for most open water channels. However, once an ice-cover forms, discharge estimation becomes more of an art than a science. Safety considerations preclude surveys during dynamic ice events, and the usefulness of water level monitoring for estimating discharge is questionable during episodes when it is uncertain how much of the water level response is due to change in flow volume and how much is due to change in flow resistance.

Given inadequate techniques for continuous monitoring of discharge through the winter period, estimates of daily discharge are prepared based on interpretation of relevant information using broadly held assumptions. Winter streamflow data production assumptions have changed little in the last 90 years. These assumptions are described fully in Hoyt (1913) and include: a positive, but inconsistent, stage–discharge relation; dominance of a uniform storage depletion curve; and a positive relationship between air temperature and discharge.

There have been relatively few attempts to verify the assumptions implicit in winter streamflow data estimation, and while these studies are generally more
successful at raising new questions than in providing answers, they do provide new information about the dynamics of winter streamflow variability (e.g. Hamilton, 1995; Hamilton & Moore 1996; Moore et al., 2000). This paper examines some evidence that challenges commonly held assumptions for winter discharge estimation. It is acknowledged that these examples are site-specific. However, these examples may lead to a better understanding of the nature of winter streamflow dynamics, which could assist in the design of monitoring programs in research watersheds that will reduce the uncertainties associated with these assumptions.

**WINTER STREAMFLOW DATA PRODUCTION ASSUMPTIONS**

**Positive stage–discharge relation**

Though the exact form of the stage–discharge curve is usually undefined for winter streamflow data estimation, the assumption that the relation must be positive is widely accepted to simplify the use of water level data for discharge estimation.

This assumption is now known to be false during episodes of formation or rearrangement of ice in the stream channel. As an ice cover forms, the ice-water interface increases the wetted perimeter of the channel, reducing flow velocity with a resultant increase in stage. Discharge actually drops during this rise in stage as water is abstracted from flow to occupy increased channel storage. Stage-up discharge–depression events resulting from formation of an ice-cover are described by Beltaos et al. (1993), Hamilton (1995), Prowse (2002), and others, but the effects of frazil ice and of changes in ice roughness on the assumption of a positive stage–discharge relationship are not well documented.

The hydrograph from the M'Clintock River in the autumn of 1994 shown in Fig. 1 shows that the timing of the discharge depression event (Fig. 1(c)) is not coincident with the stage-up event (Fig. 1(b)). The reason for this discordance is likely to be related to the upstream progression of the ice-front increasing the total volume of flow abstracted to satisfy channel storage over a period of about 2 weeks. The flow reduction is probably exacerbated by the formation and decay of frazil ice in the cross-section (Fig. 1(a)). The ice cover at the gauge provides a surface for accumulation of frazil ice generated in open water sections upstream of the gauge. The upstream progression of the ice front closes off the source of frazil and the frazil accumulation at the gauged section is lost to erosion. The flow obstruction from frazil can be substantial, particularly during episodes of maximum frazil generation in the early winter. This obstruction to flow can magnify the volume of a discharge depression event, may alter the timing and duration of the event, and could disappear entirely before surveys can be made that would confirm the presence of frazil ice as a factor in discharge estimation for the event.

The vertical dashed lines connecting the stage and discharge hydrographs in Fig. 2 are provided to mark instances where a negative relation between stage and discharge has been observed during break-up. Photographs are provided to show the condition of the ice cover associated with the event. As the ice decays, channel storage is released, causing a transient increase in discharge as stage drops due to the reduction in frictional resistance to flow. Prowse & Carter (2002) found that water released from
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Freeze-up

- Fig. 1 M’Clintock River freeze-up data from the fall of 1994. (a) Area of cross-section obstructed by frazil ice (left axis, top); (b) water level hydrograph (right axis) with observed water level and near-stream piezometric head; (c) measured discharge hydrograph (left axis); and (d) difference in elevation between channel stage and piezometric head (right axis, bottom). The vertical line marks the onset of formation of ice cover.

Ice-induced hydraulic storage may account for 15–19% of spring freshet volume in the Mackenzie River.

A substantial increase in the stage hydrograph for M’Clintock River in March 1995 is shown in Fig. 3. Horizontal dashed lines are provided to show that the discharge in March is lower than it was in January, whereas channel stage is about 0.2 m higher in March than in January. The increase in stage in March is, at least in part, due to an increase in the roughness of the ice–water interface caused by ripples formed.
Fig. 2 Discharge and water level hydrographs for (a) the Takhini River and (b) the M’Clintock River during the spring of 1995. The vertical dashed lines indicate measurements that show a rapid increase in discharge coincident with a rapid drop in stage. The pictures to the right show the ice condition during the break-up period.

as the ice warms and softens (Alford & Carmack, 1988), resulting in a negative stage-discharge relation during the late winter.

A modest increase in discharge in March may be associated with an increase in runoff, perhaps from early snowmelt, but the rapid increase in stage caused by increased ice roughness is probably diverting most of that early runoff into channel storage.
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Fig. 3 Stage and discharge at M’Clintock River near Whitehorse during the spring of 1995. The horizontal dashed lines are for reference of the relative difference between January and April stage and discharge.

**Uniform storage depletion curve**

The assumption of a uniform storage depletion curve is useful during episodes of sustained sub-freezing temperatures streamflow, when depletion of groundwater and/or lake storage volumes result in a smooth concave-up hydrograph shape. The acceptance of this simplifying assumption means that only one or two discharge measurements are necessary to estimate a hydrograph for any period of sustained sub-freezing temperatures.

The assumption of uniform lake-storage depletion is broadly accepted. However, it may not be safe to assume that discharge from a lake is also uniform during the winter season. The lake stage hydrograph shown for Kusawa Lake, Yukon Territory (Fig. 4) shows a characteristic concave-up shape, but the photographs of the lake outlet ice conditions show that the hydraulic efficiency of the lake outlet changes throughout the winter. Hence, lake discharge throughout the winter will respond in part to lake stage, but could also be sensitive to the extent of ice cover over the lake sill.
Fig. 4 Kusawa Lake, Yukon Territory. Extent of the ice cover at the lake outlet and lake stage hydrograph.
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The assumption of uniform groundwater storage depletion may not be valid if there is stream–aquifer interaction. Several authors have identified stream–aquifer interaction as a mechanism contributing to winter streamflow variability (e.g. Chin, 1966; Kane, 1981; Hamilton & Moore, 1996), but the importance of this mechanism remains unclear.

In the plot of the differences between near-channel piezometric head and channel stage shown in Fig. 1(d), a positive value indicates a positive hydraulic gradient between a near-stream piezometer and the stream channel. Negative values show that a negative hydraulic gradient is caused by stage-up, which persists until channel stage returns to a near-freeze-up level. Groundwater discharge during the winter season will be sensitive to the changes in the near-stream hydraulic gradient, which is responding to changes in the condition of the ice cover.

Positive relation between air temperature and discharge

The assumption of a positive relation between air temperature and discharge is based on the notion that, even during episodes of sustained sub-freezing temperature, winter streamflow is sensitive to changes in air temperature. This assumption is used subjectively to account for discharge measurements that don’t plot on a smooth recession curve and to identify the end of the storage depletion recession. Hamilton et al. (2001) examined the residuals of storage depletion curves from three winters at Wolf Creek, Yukon Territory plotted against 1-, 3- and 5-day antecedent air temperature and found that the regression statistics were not statistically significant.

DISCUSSION AND CONCLUSIONS

A minimal effort to collect streamflow data during the ice-covered season is usually based on the argument that the hydrological processes of rainfall runoff and snowmelt are controlled by sustained sub-freezing temperatures, leaving storage depletion as a dominant and predictable source of winter streamflow variability. However, channel storage processes and interactions between channel storage and lake and groundwater storages may be more dynamic than is typically assumed, and some of these storage exchanges can invalidate assumptions implicit in winter streamflow calculations.

The examples provided in this paper are specific to the local circumstances, hence it is impossible to generalize from these examples what magnitude of winter streamflow uncertainty could be expected for other basins, or even for other locations within the same basin. Whereas discharge responds consistently to the integrated runoff from the landscape upstream of the gauging station during the open water season, discharge at any given stream reach can be substantially modified by local conditions during the period of ice-effect. Interpretation of runoff volumes for water balance calculations should be provided in the context of these uncertainties, and further research is required to develop predictive knowledge for winter streamflow variability.
REFERENCES


