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# River-ice effects on the estimation of the annual low-flow in un-gauged cold-region basins

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The lowest flow in any given year is typically at the end of the winter in most cold, nival regimes. The dominant sources of low-flow are from groundwater and lake storages that have been monotonically depleting since the onset of the winter. It is generally accepted that drainage area can be a reliable predictor of low-flow, given that storage availability is assumed to be a simple function of drainage area in any homogeneous landscape. A regional low-flow prediction equation was examined for the interior region of Yukon Territory. Of 31 stations in this region, there were two stations that clearly did not fit the regional pattern. WSC technologists report a history of icing events at these two sites. A hydrometric survey was conducted, involving nine sites on the Koidern River, in late March, 2006. The local-scale drainage area – base flow relation did not conform to the regional relation. In fact, if only the five largest stations in the local-scale study are considered, the slope of the local-scale relation would actually be negative. Icings were observed at, or near, each confluence along the Koidern River. Rather than accumulating flow from each tributary, the Koidern River apparently loses flow to ice production or to hyporheic exchange flow at these ice dams.

## 1.0 Introduction

Sub-Arctic streamflow typically reaches a minimum at the end of the cold season just before the onset of spring melt. Late-winter streamflow is relatively unaffected by meteorological influences, leaving storage elements in the contributing area as the dominant source of flow. The depletion of water from these reservoirs is expected to form a smooth, concave-up, recession curve (Tallaksen, 1995.)

Storage reservoirs supplying late-winter flow in much of the Sub-Arctic are dominated by groundwater. Lake storage is an important factor in some watersheds, but the influence of lake storage is generally greatest in the early winter. With the exception of lakes that have a very high volume of active storage, the daily rate of change in lake stage approaches zero by late-winter; at which point lake-outlet discharge is only slightly greater than lake inflow. An empirically-determined relation between drainage area and late-winter streamflow is expected to have high predictive power for any un-gauged landscape that is similar to the watersheds for which data are available.

On this assumption, there is little perceived urgency to collect winter streamflow data for sub-Arctic streams in spite of the growing need to understand low-flow hydrology. A relatively small number of gauging stations over a sufficient range of scale should yield useful predictions of late-winter flow for any, sufficiently similar, un-gauged landscape.

A reliable supply of water during the low-flow season is a boundary condition for aquatic life and this boundary often overlaps with conditions that are otherwise conducive to biotic productivity (e.g. spawning beds). Late-winter water availability can be a limiting factor for a number of aquatic populations (Prowse, 2000); hence knowledge of late-winter flow conditions is needed to protect these populations from anthropogenic influences.

The reliability of predictions of low-flows in Sub-Arctic, un-gauged, watersheds is of particular importance for the development of linear projects such as pipelines. There are several such projects that are actively being developed or planned, including some very large ones such as the Mackenzie gas pipeline and the Alaska gas pipeline. The number of stream crossings for these projects is very large with respect to the number of gauging stations in the region.

Whereas pipelines are, arguably, most at risk from high-flow conditions at stream crossings, the aquatic environment may be most at risk during low-flows at pipeline crossings. A number of engineering decisions need to be made at each crossing to design a solution that optimizes pipeline security while minimizing risk to the environment. Engineering solutions that protect against flood damage include bridging, trenching and directional drilling. These solutions distance the pipeline from proximity to the stream-bed, which also serves to reduce potential impacts of the pipeline on the in-stream environment during the low-flow season. Stream crossing construction is typically scheduled to occur over the winter season.

Knowledge of low-flows at un-gauged locations is therefore required both for design and planning purposes. The aquatic environment is more likely to be sensitive to the presence of a crossing at flows near some minimum threshold that is needed to maintain connections between over-wintering habitats. Therefore, a distinction between no-flow and more-than-enough-flow becomes critical in designing a crossing. Planning the construction of crossings requires knowledge of low-flow volumes to ensure safe working conditions and adequate capacity for storing or diverting flow, while maintaining in-stream flow needs.

Williams and Van Everdingen (1973) estimated groundwater discharge rates in the order of 3 to 5 l/s in the zone of discontinuous permafrost. One would expect late-winter streamflow rates to be slightly higher than this in watersheds with significant lake storage and some negative variation from this relation in accordance with local differences in the rate that water is abstracted from flow for ice production.

Low-flow information has value for engineering design and planning purposes and this information is frequently needed at un-gauged locations. Whereas at-site measurements will become available as a project progresses, the environmental assessment process requires such information in advance of the detailed design phase. When new measurements are obtained, there is a need to evaluate whether the difference between observation and prediction is consistent with the variation within expected inter-annual variability or whether the site is atypical for the region.

A simple field survey to examine the applicability of a regional low-flow relation at a local scale was made in the spring of 2006 in Southwest Yukon. The results of this survey are presented after a brief description, in the next section, of the methods used. The concluding discussion of the unexpected results attempts to yield insight into local scale effects of river ice on hydrology and aquatic ecology.

## 2.0 Methods

The regional analysis of low-flow is based on the interior region described by Janowicz (1991), who divided Yukon Territory into four homogenous regions for low-flow prediction. Within this zone, Janowicz reports that basins smaller than 500 $km^2$ may occasionally experience zero flow and that 5,000 $km^2$ is the lower limit for 100-year low-flow events.

The annual minimum daily flow reported in the Hydat database for Yukon River stations in this region is typically in late March or early April though dates as early as December and as late as May are reported. These data are, with few exceptions, flagged with a ‘B’ which indicates that they are subjective estimates of flow under backwater conditions. The evidence in support of these estimates is inconsistent both at-a-site, amongst years and in-a-year amongst stations. In some cases, the estimates may be based on relatively frequent under-ice measurements but in many cases the estimates may be based on very few under-ice measurements. In some cases, continuous stage record may be available as a guide to flow estimation but in many cases, stage record is unavailable because of problems with gauging in the Sub-arctic winter (Hamilton, 2003). Nonetheless, this published record is what most engineers would turn to as a source of low-flow information.

The Yukon River low-flow information was filtered to select annual daily minimums that occurred in the months of March or April. These 520 low-flow estimates from 31 stations are shown in Figure 2 plotted against the published drainage area for each station. Estimates of zero flow are shown at 0.001 $m^3/s$ so that a log scale can be used. Two stations, shown with open circles, are clearly non-compliant with the regional trend. A 7-day low-flow equation derived by Janowicz (1991) is shown as a solid line, which can be compared to the two dashed lines that show the range of discharge expected from groundwater sources in this region (Williams and van Everdingen, 1973).

The field study area is the Koidern River in the Southwest Yukon (Figure 1). The Koidern River joins the White River downstream of the study area, which then drains into the Yukon River. The Koidern River was chosen because it lies on the route of the proposed Alaska gas pipeline and it has relatively easy to access from the Alaska Highway. The tributaries and main-stem of the Koidern River traverse a representative variety of Sub-Arctic landscapes including alpine, boreal forest and wetlands and is in a zone of discontinuous permafrost.

Discharge measurements were made at seven locations on the main stem of the Koidern River and near the mouth of two tributaries, as shown in the schematic (Figure 3), over the period from March 28 to 31, 2006. Standard WSC measurement methods using a Price 622 winter pattern meter suspended by ice rods were used at eight of the nine sites (Terzi, 1981). An open lead at the Koidern River above Koidern #1 site prevented the use of the standard equipment. At this site, dilution gauging, following the salt slug injection method described by Moore (2005) was used. At the two tributary sites, determination of zero flow was confirmed by verification at three or more cross-sections within the stream reach. In most cases, the holes in the ice at zero-flow sections were ice-to-bed, but in some cases the ice cover was over stagnant water or compacted slush. In the case of stagnant water, zero-velocity was assessed as a lack of sufficient force to turn the current meter one revolution in a sample period of a minute or more.

## 3.0 Results

The discharge and the specific conductance of the water at each station in the field study are shown in the context of the drainage relationship in the Figure 3. These measurements plotted against drainage area are shown along with the two dashed lines representing the range of groundwater discharge that could be expected in this region (Williams and van Everdingen 1973) and the mean 7-day low-flow regression of Janowicz (1991) for the Yukon interior region in Figure 4.

## 4.0 Discussion

Winter streamflow provides a particular challenge with respect to predictions of low-flow in un-gauged landscapes. Whereas a regional low-flow equation such as the one shown in Figure 2 is generally applicable, the at-site, inter-annual variability is in the range of 0.5 to 1.5 orders of magnitude for well-behaved sites and can exceed three orders of magnitude in special cases. This variability is difficult to explain on the basis of groundwater supply alone. Some of the observed variability is likely due to river ice conditions that vary from winter to winter.

The two stations shown as open circles in Figure 2 are (09EB003) Indian River above the mouth, and (09AH003) Big Creek near the mouth. These stations are known to WSC technologists as being stations with a history of excessive ice production (Palfreyman, pers. comm.). The amount of ice could impact on the reliability of measurements at these sites causing some of the observed variability. The pattern of ice development may affect where, along the stream reach, the measurements are taken. Alternatively, the pattern of ice formation may regulate the groundwater-surface water interaction, resulting in the gauged reach being actively used for conveyance or, perhaps, disconnected from the groundwater system resulting in such large inter-annual variability.

It is important to be able to assess the validity of low-flow predictions for the purposes of environmental assessment. If a prediction is that there will be no-flow, when in fact there is flow or if a prediction is that there is more than enough flow, when in fact there is barely enough flow, construction activities could result in adverse consequences before the error is discovered. It is also important to be able to assess the transferability of gauged information. It is frequently necessary to take a measurement at one location to infer streamflow at another location. This assumption may not be true if river ice is actively interacting with groundwater and controlling the in-channel conveyance of water.

The longitudinal discharge survey of the Koidern River supports this notion that patterns of river ice formation may be linked to groundwater discharge. Stagnant water impounded by river icings shows a much higher specific conductance than water in the rapidly flowing reaches of the river. And, if only the five main-stem stations in the lower part of the watershed (Figure 4) are considered, there is an unexpected negative relation between drainage area and discharge. However, the volume of discharge at these sites is in the range predicted by the regional relation (Figure 4) even though the discharges at the four smaller tributaries are atypical.

Extensive icings were observed at the confluence with Wolf Creek, between Koidern above Koidern #1 (Figure 5) and Koidern at Lake Creek Campground and at the Edith Creek Confluence. The ice cover at these icings was, in most places, deeper than we could drill with our equipment, which extended to at least 2m. In one case, at the confluence of Wolf Creek, water under pressure geysered out of the holes drilled in the ice. These icing contrasted with extensive open leads at Koidern #1 (Figure 6) and also with the Koidern River at Lake Creek Campground where the average ice thickness was 0.44m but was bridged over a 0.25m air pocket over the water surface, where several river otters were observed accessing the river through cracks in the ice. The un-supported ice at this location was strong enough to span a 7.5 m wide channel over a length of about a hundred meters.

The icings were most often located at the confluence with smaller tributaries (Figure 2), which may mean that these icings have a geomorphologic causal factor. It is apparent that the river does not accumulate flow incrementally as a function of drainage area alone. There appear to be reaches that produce discharge in ‘typical’ volumes but in-between there are losses of water, which is abstracted to build ice. The static head upstream of these ice dams may reach a point that returns water to streambed gravels to flow underneath the ice dams and re-emerge to a water-starved downstream reach where the static head is much lower.

The data collected on this study are insufficient to make any conclusions about the true dynamics of this stream and are even less suited to make broad generalizations about river ice processes and groundwater interaction. However this data does indicate that additional study is required to determine how common this type of unexpected longitudinal variation is in winter environments. The data also show that the location, along a stream, that a winter measurement is made can have a very large effect on the results.

Local scale variability can be very important. The abundance of river otters within short distances of zones of zero flow show that habitats that are very close to the edge can be very productive. It would be very useful to know more about the meteorological and geomorphic controls on these river ice phenomena. The ice may be acting as a gate-keeper for groundwater and if the presence and volume of ice is predictable from winter to winter then groundwater discharge zones, which are essential winter habitat, would also be predictable.

The adequacy a sparse network for predicting flow at the hundreds, or thousands, of stream crossings for a linear project is also questionable. The existing hydrometric network is designed largely on the notion that the sites are regionally representative. However, the notion of a representative ice regime has never been addressed. The stations in the network may be under-sampling the full range of ice-regimes in the region. Extensive late-winter surveys may help to better understand the relative distribution of typical and atypical ice regimes.

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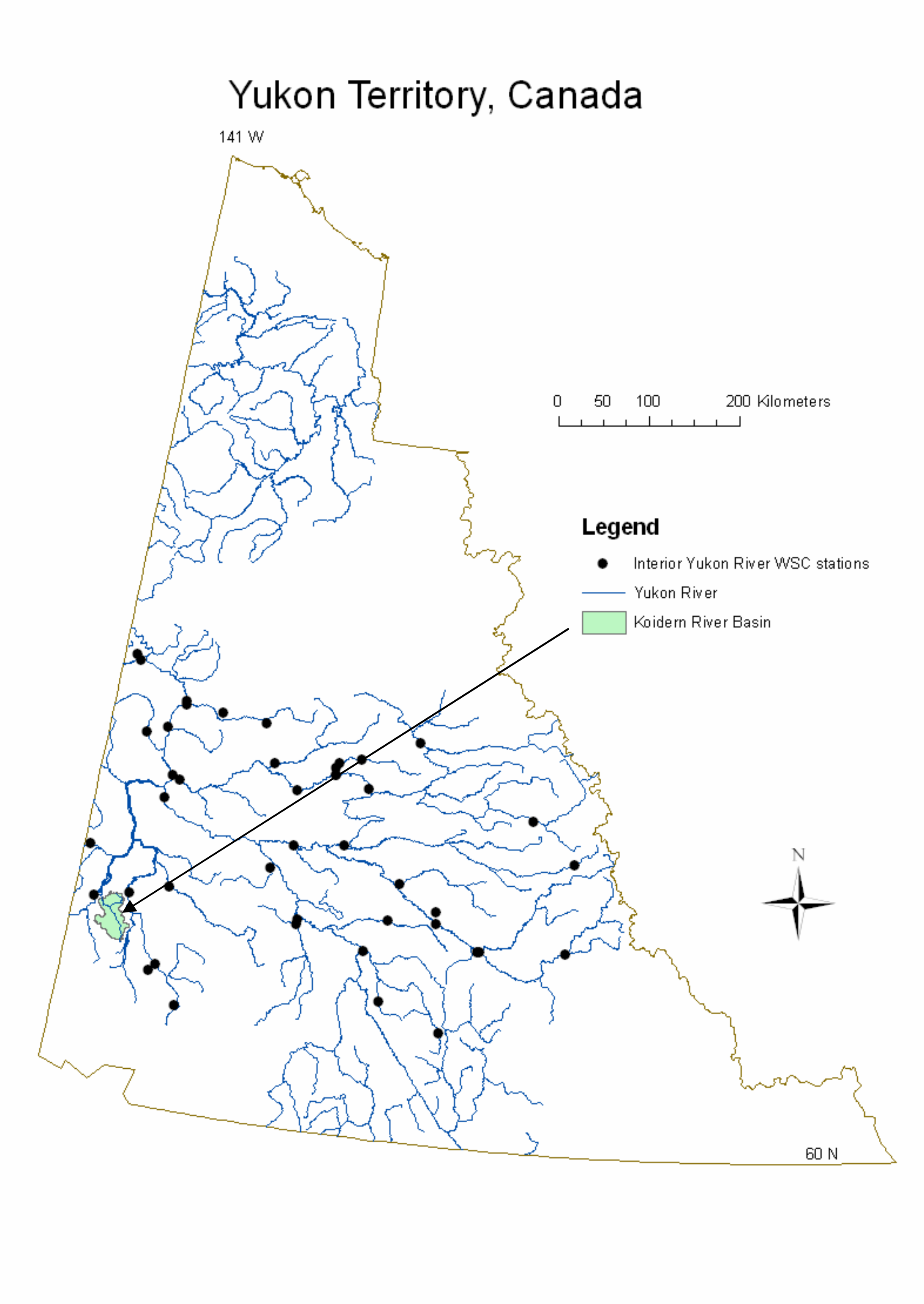


**Figure 1:** Map of the Yukon Territory showing the Yukon River, the location of WSC gauges used for regional analysis and the location of the Koidern River basin.

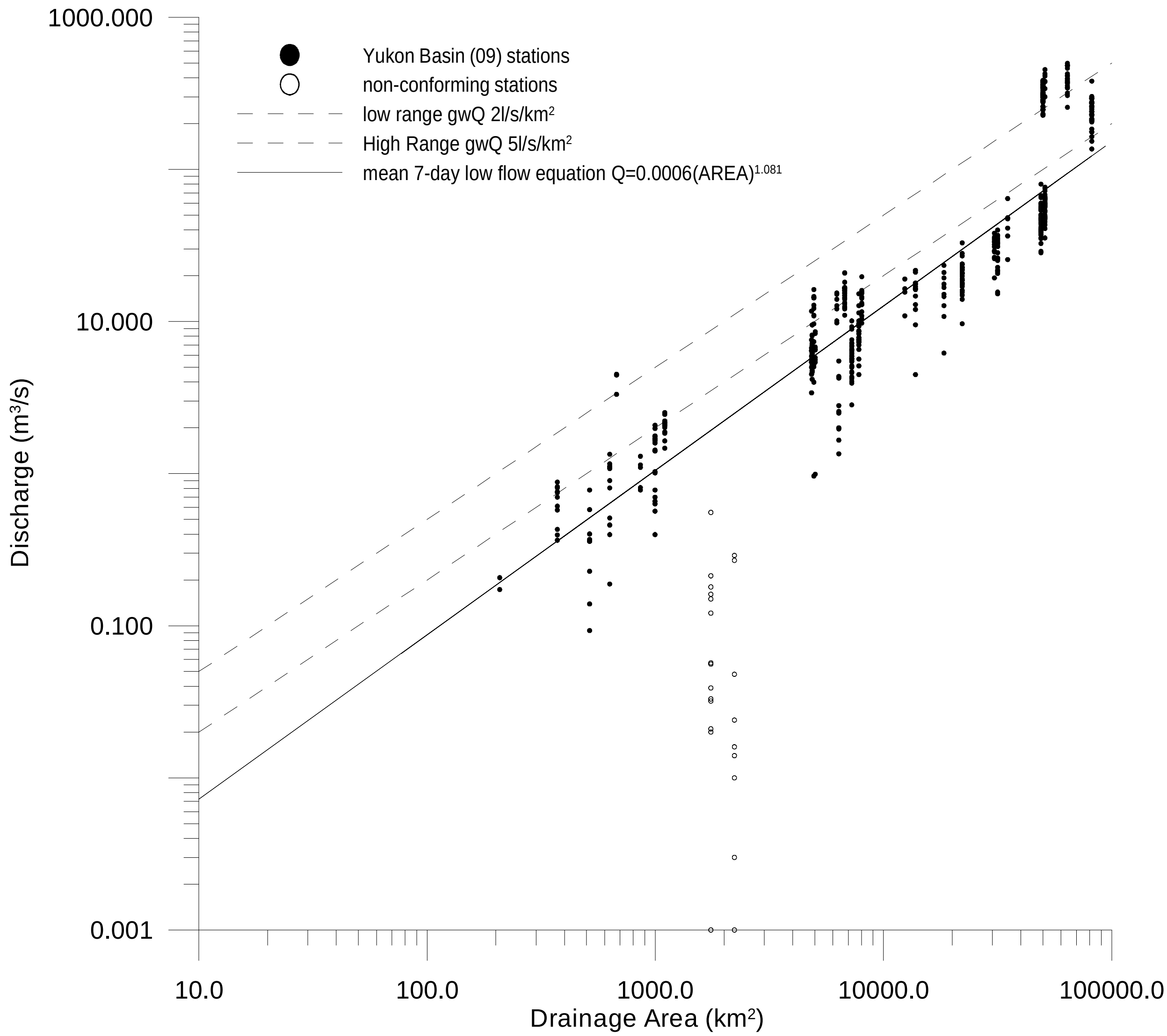


**Figure 2:** Annual low-flows from Hydat database closed circles are annual minima from the Hydat database and open circles are minima from stations in the Hydat database that are obviously inconsistent with the regional trend. Dashed lines are the estimated ranges of groundwater discharge (Williams and van Everdingen, 1973) and the solid line show the mean 7-day low-flow equation of Janowicz (1991) for the interior region.

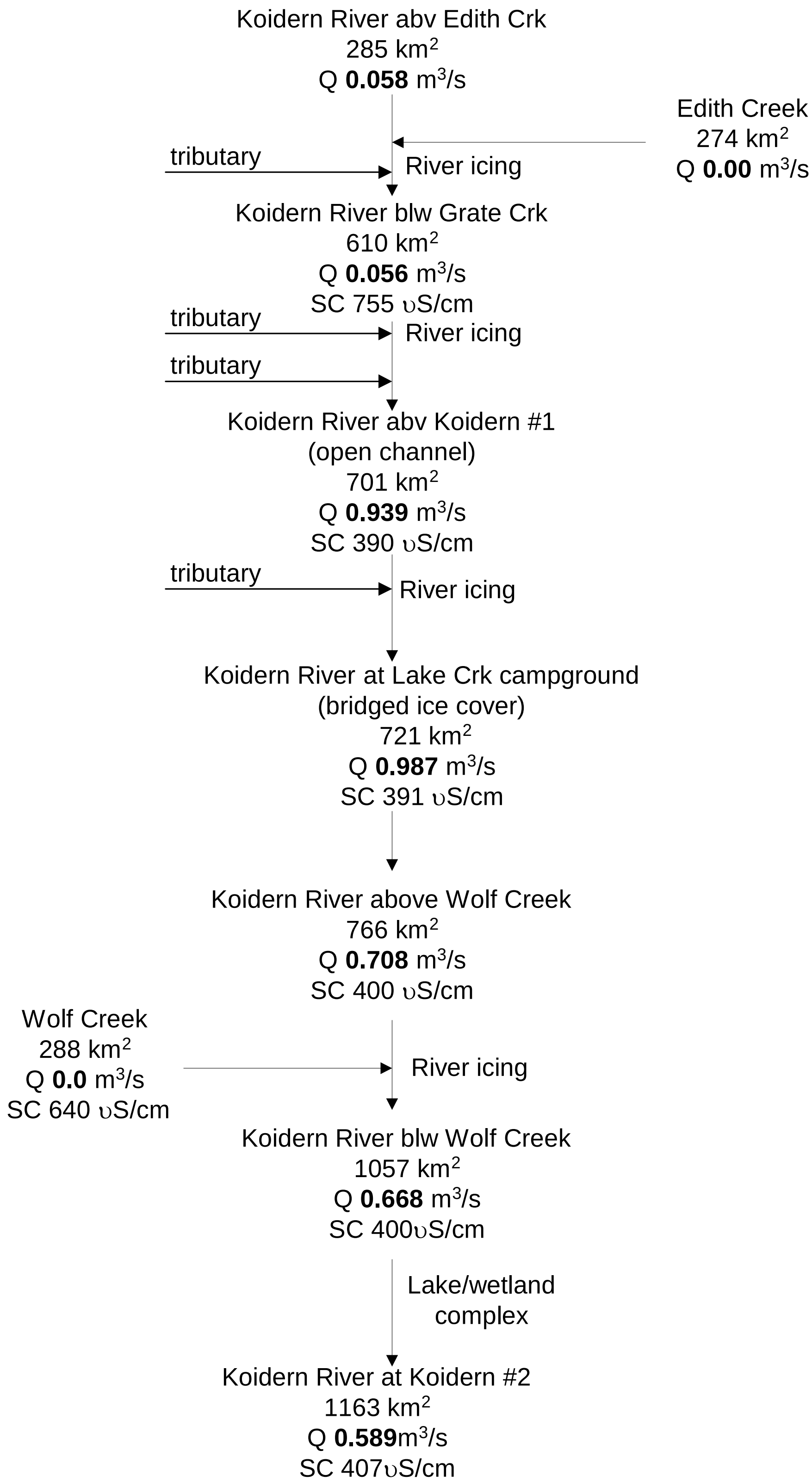


**Figure 3:** Schematic showing the survey cross-sections relative to the main stem, drainage area, discharge, and specific conductance

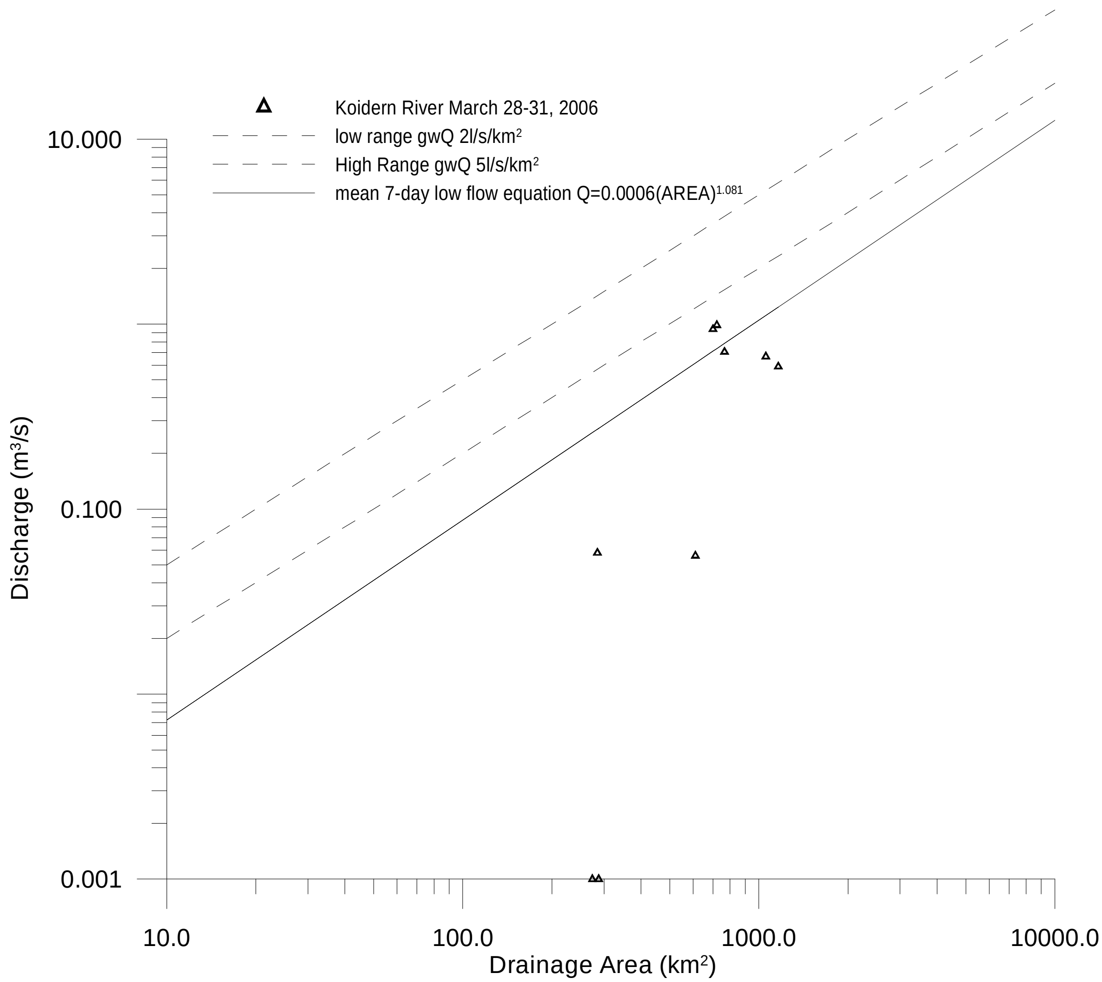


**Figure 4:** Koidern River discharge measurements against drainage area. The dashed lines represent the expected range of groundwater discharge (Williams and van Everdingen, 1973) and the solid line shows the 7-day low-flow equation (Janowicz, 1991). Zero flow is plotted as 0.001 $m^3/s$

**Figure 5:** River icing between Koidern at Lake Creek Campground and Koidern above Koidern #1. The width is approximately 20m and the ice thickness is approximately 2m thick

**Figure 6:** Open lead at Koidern above Koidern #1. This picture was taken a few hundred meters upstream of the picture shown in Figure 5.