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Winter Hydrometry: Real-time data issues

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The Canadian winter has a profound influence on winter streamflow and water levels. Unfortunately, the methods and technologies used for collection of streamflow and water level data are not robust to winter operations. This has not has not been seen as a serious problem in the past because the publication schedule for hydrometric data allowed for extensive *post hoc* censoring and modification of the data using subjective interpolation techniques for data estimation. Canada, like many countries, is now publishing hydrometric data in real-time on the world-wide-web. One of the risks of disseminating data as soon as it is acquired is that there is little or no opportunity to scrutinize, censor, or modify erroneous data. This risk is particularly acute in the winter season when there is a high rate of cold-temperature related equipment failures that may readily be confused with valid data during episodes of re-arrangement of ice in the stream channel. In this paper, data taken from Environment Canada's real-time web site for the period from October 1, 2001 to May 31, 2002 is examined. The reliability of the data was estimated as a fraction of the data published in real-time that can be considered valid. The reliability of the data for this eight-month period was 48% for water level and only 16% for discharge data for 11 stations located in the Yukon Territory. The requirement to provide hydrometric data that is not only accurate but also timely creates a new urgency to solve some of the problems of winter hydrometric operations.

1.0 Introduction

Ice-affected streamflow accounts for 18.7% of all the hydrometric data published in Canada by the Water Survey of Canada (WSC). WSC flags data affected by ice cover with a ‘B’ in discharge publications such as the Hydat CD-ROM. The number of station-days of data produced by the WSC up to and including the year 2000, by province is provided in Table 1, along with the number of days that have been flagged with a ‘B’. That winter streamflow is important from a statistical analysis and engineering design perspective can be seen by the frequency of occurrence of annual extremes flagged with a ‘B’ as shown in the right-most columns of Table 1. This estimate of the importance of ice on the Canadian hydroscape is likely an under-estimate because of a distinct latitudinal bias in the density of hydrometric stations in the WSC network. The map of persistence of ice at hydrometric stations in Figure 1 shows the prevalence of ice in the Canadian landscape. In contrast, the histogram in Figure 1 illustrates the bias in the network toward streams with minimal ice effect.

Table 1: The Water Survey of Canada data inventory

Province	Station-days	‘B’ days	% of record	% of low extremes	% of high extremes
BC	8 627 563	1 225 202	14.2	34.6	0.1
ON	7 105 110	1 041 975	14.7	11.9	7.2
AB	5 037 259	1 068 452	21.2	55.9	11.4
PQ	4 895 833	890 388	18.2	26.3	1.2
SK	3 320 473	545 186	16.4	50.0	26.7
MB	2 664 249	672 512	25.2	64.6	26.5
NF	1 042 414	192 465	18.5	25.0	4.4
NB	1 022 985	255 992	25.0	23.6	7.4
NS	836 907	86 935	10.4	1.9	3.6
NT	680 209	293 933	43.2	75.8	17.0
YT	666 579	341 715	51.3	92.6	2.2
NU	269 753	150 314	55.7	89.8	11.4
PEI	140 970	13 667	9.7	10.2	10.8
TOTAL	**36 310 304**	**6 778 746**	**18.7**	**38.0**	**9.3**

Hydrometric surveys and discharge computations for the ice-covered period are based on basic principles established by scientific investigations conducted nearly a century ago (e.g. Barrows and Horton, 1907, Hoyt, 1913). Even though winter hydrology and hydraulic process are now understood to be much more complex than was previously assumed (e.g. Prowse and Gridley, 1993), and many techniques for winter streamflow data production have been investigated (e.g. Melcher and Walker, 1992), the most reliable operational method of producing winter streamflow estimates in use today is subjective interpolation by climatic comparison (Rosenberg and Pentland, 1966). This method is more art than science and is highly dependant on the skill and experience of the technologist. Subjective interpolation has no specific requirement for continuous *in situ* data collection, but does require extensive, *post hoc*, interpretation with a resultant delay in data availability and a lack of reproducibility (Hamilton et al., 2001).

Changes in water management practice in Canada are creating an increased demand for real-time hydrometric data and there is also increasing risk of litigation stemming from water use practice during the low flow season. Clearly, the need for timely and verifiable year-round hydrometric data has never been greater than it is now.

The publication of water level and discharge data in real-time provides a new and rich source of information for engineers, scientists, and water resource managers. However, distribution of data as it is received has the potential to cause confusion amongst end-users who are not accustomed to the disruptive effects of ice on stage-discharge relations used to derive discharge estimates. Traditional, *post hoc*, publication of hydrometric data allows for intensive censoring and modification of the data before the data-consumer gets to see it. As a result, there are relatively few data-consumers with the ability to correctly interpret real-time hydrometric data throughout the winter period.

The United States Geological Survey (USGS) web site http://waterdata.usgs.gov/nwis/rt which provides water level and discharge data for about 1.5 million stations provides the warning:

> ***Data effected by ice conditions***
>
> *During extreme cold winter weather, river stage may be affected by ice. This results in incorrect discharge data being computed from the stage data. Some of the station data-graphs may be turned off during the ice-effected periods.*

The USGS approach for publishing real-time data for northern climates requires frequent visual inspections of the data by field staff knowledgeable about the local site conditions.

The Canadian real-time data site: http://scitech.pyr.ec.gc.ca/waterweb provides real-time data for approximately 1200 stations across Canada. Many of these sites are ice-affected for at least several months each year. At the present time, the data provided on this site is un-censored raw water level and automatically derived discharge data. Ideally, a system to flag or censor erroneous data should be developed. However, the design of such a system presumes an ability to characterize and distinguish the various pathologies of ice effect (i.e. valid water level, invalid discharge) from instrumentation pathologies (invalid water level, invalid discharge).

A description of hydrometric monitoring technologies in the next section provides context for interpretation of the pathologies described in section three. The consequences of these pathologies are discussed in section four leading up to the concluding remarks which connect these problems with issues of real-time hydrometric data publication.

2.0 Hydrometric monitoring

Hydrometric operations are dependant on continuous water level record. A typical monitoring configuration consists of some sort of water level sensor connected to a data logger, with the data logger connected to a telemetry device.

Water level is sensed either by direct linear measure or by transformation of a measurement of pressure. A typical linear measurement device records the difference between a reference elevation and a float in a stilling well. This distance is sensed by the shaft rotations of a pulley over which a wire connecting the float to a counterweight rides. These shaft rotations are either mechanically translated into pen movements on a strip chart recorder, or are transformed into a digital signal by an incremental shaft encoder with output stored on a data logger. Stilling wells are used to isolate the float from external environmental forces such as wind or wave action. Float sensors are a very reliable and relatively inexpensive technology for water level measurement. Unfortunately, this technology requires a free water surface, which is virtually impossible to maintain at remote northern locations through extended period of cold weather. Acoustic transducers, radar, and laser measurement devices are examples of linear measurement technologies that have been tried but are considered to be too expensive or too difficult to use to be operationally practical for continuous monitoring in remote locations.

Pressure sensors are the *de facto* standard for northern hydrometric monitoring operations. The principle of these devices is that a pressure differential between the some point on the bottom of the river and ambient atmospheric pressure can be transformed to a linear measure of the height of a column of water by a simple density conversion (1 pound per square inch (psi) of pressure = 70.3 cm of water at 4 ^{o}C). The pressure differential is sensed and transformed into an electrical signal by the deflection of a diaphragm exposed to water pressure on one side and ambient air pressure on the other. Pressure sensors may be either submersible, in which case a vent tube to a chamber adjacent to the diaphragm is used to establish the reference pressure, or of a gas purge type. The gas purge type pressure transducer is operated from the relative safety of a gauge house on the stream bank. Compressed gas is fed through a constant differential pressure system connected to an orifice on the streambed by plastic tubing. The transducer is plumbed into the downstream end of the constant differential pressure system so that it is exposed to any change in pressure that occurs at the orifice.

Winter operation of float sensors can be jeopardized either by the formation of ice on the free water surface or by freezing of the intake pipes connecting the stilling well to the stream channel. Submersible transducers are exposed to risks of freezing in shallow rivers; anchor ice during the ice formation period and ice scour during break-up. The data from submersibles is jeopardized if the vent tube becomes blocked for any reason. The data from gas purge transducers is at risk if there are any leaks or blockages in the pressurized system. These leaks are most likely to occur during cold temperatures as a result of differential contraction rates of materials at junctions in the system. Blockages are most likely to occur in cold temperatures as a result of moisture accumulating at low points in the tubing and subsequently freezing, or by ice forming over the orifice.

3.0 Winter hydrometric data pathologies

In this section, data taken from the real-time web site (http://scitech.pyr.ec.gc.ca/waterweb) is examined. The 11 selected stations are all from the Yukon Territory for the winter of 2001-02. Three climate stations are used to provide representative air temperature and precipitation data for diagnostic comparison. The location of the hydrometric stations with respect to the climate stations is shown in Figure 2. These stations range in size from 194 km^2 to 150,000 km^2 (Table 2), are representative of humid (482 mm annual runoff) through to dry (92 mm annual runoff) climates and all of the stations are ice-affected for at least six months of the year (http://scitech.pyr.ec.gc.ca/climhydro). The Yukon Territory was selected for this study because it has the highest density of stations for which winter data collected in real-time is available.

Table 2. Station characteristics

Station name	number	Drainage area (km^2)	Mean annual runoff (mm)	Percent annual ice cover
Alsek River above Bates Creek	08AB001	16,200	426	51
Beaver River below Matson Creek*	09DB001	---	---	---
Giltana Creek near the mouth	08AA009	194	92	48
Klondike River above Bonanza Creek	09EA003	7,800	256	55
Liard River at upper crossing	10AA001	33,400	353	51
Nisling River below Onion Creek*	09CA006	---	---	---
Old Crow River near the mouth	09FC001	13,900	100	66
Pelly River at Pelly Crossing	09BC001	49,000	253	52
Stewart River near the mouth	09DD003	51,000	285	55
Tatshenshini River near Dalton Post	08AC002	1,750	482	48
Yukon River above White River	09CD001	150,000	255	53

** Statistics have not been computed for the Beaver River and Nisling Rivers because these have only been in operation for a short period of time*

3.1 Ice-affected water level and discharge pathologies.

The formation of an ice cover increases the frictional resistance to flow in a stream channel causing a reduction in stream velocity. This velocity reduction typically causes an increase in cross-sectional area (stage-up) for any given volume of discharge. The stage required to convey a given volume of discharge is also a function of the volume of ice in the cross-section in the channel that is not contributing to flow regardless of the form of that ice (i.e. surface ice, frazil ice, anchor ice etc.). The formation, decay or re-arrangement of ice at any given cross-section may occur gradually over time by thermal processes or abruptly by hydraulic processes.

Discharge estimates, based on a stage-discharge relation calibrated during the open water season, are not valid during the period of ice-effect as can be seen in the hydrographs in Figures 3 and 4. There were two measurements during the ice-affected period at the Alsek River (Figure 3), shown with open circles. The first measurement, in January, was 46.2 $m^3 \cdot s^{-1}$, whereas the computed discharge was 252 $m^3 \cdot s^{-1}$, for an error of 445%. The second measurement, in May, made with partial ice-cover conditions was 57.1 $m^3 \cdot s^{-1}$. A computed discharge was not possible for this measurement because the stage was below the bottom of the stage-discharge rating. The computed discharges coincident with two winter measurements made at the Klondike River (Figure 4), in January and April, were 814% and 1020% of measured discharge.

Discharge can also be impacted by the volume of water abstracted from flow to satisfy up-stream channel-storage requirements resulting from stage-up. This effect can be seen in the hydrograph for Klondike R, where there is a sharp reduction in water level in late-November followed by a subsequent recovery.

Stage-up events can been seen in the water level hydrographs for the Alsek, Klondike and Liard Rivers shown in Figures 3, 4 and 5. Stage-up at the Alsek River (Figure 3) occurred in two sequential events. The first event started in early November, as temperatures dropped below –10 ^{o}C. Water level increased rapidly and erratically until a rapid drop occurred in mid-November. The second event started in late-November when temperatures dropped below –20 ^{o}C. Stage-up on the Klondike River started in late-October but was dominated by a very rapid increase in mid-November followed by a period of instability. Stage-up on the Liard, in early-November, was abrupt but coherent with very little associated instability.

The three hydrographs in Figures 3, 4, and 5 show distinctly different ice-decay pathologies. The Alsek River (Figure 3) under-went a rapid decrease in water level in late-April. The Klondike River (Figure 4) had a very rapid increase in water level in early-May, followed by several weeks of instability. The Liard River (Figure 5) ice decay resulted in a week of stage instability in mid-May of a magnitude far less than seen at Alsek or Liard.

Re-arrangement of ice in the stream channel produces some of the most extreme rates of change in water level. The hydrograph for the Alsek River (Figure 3) shows a drop in stage on November 17 at a rate of 0.32 m/h. The data spike on November 5 occurred at a rate of 0.73 m/h. The water level fluctuations related of re-arrangement of the ice cover at Klondike River (Figure 4) are generally more cyclical than seen at Alsek, with the exception of the event on May 10 when the rate of change reached 0.5 m/h on the rising limb and 1.02 m/h on the falling limb.

3.2 Cold-temperature pathologies

Cold temperatures and ice can affect monitoring equipment in ways that produce a number of distinctive pathologies. These are symptoms of invalid data that may appear reasonable on first inspection, especially during the winter season when ice-effects can cause the true hydrograph to be quite erratic.

Frozen orifices or blockages in the pressure tube will cause the pressure sensed by the transducer to increase rapidly. The hydrograph for Beaver River (Figure 6) is symptomatic of a blockage of this sort, which occurred at the end of a long cold snap in mid-December. One would expect that the pressure would remain stable if the blockage was complete, but this particular example is complicated by an intermittent pressure leak that first became evident in mid-November.

Frozen stilling wells result in a straight-line trace as can be seen in the record for Giltana Creek (Figure 7). There are a number of data spikes in this record that appear to be spurious artefacts of the shaft encoder.

Pressure leakage problems can present in a variety of forms. At Stewart River (Figure 8), an intermittent leak in late winter is seen as a series of events that are consistently erratic. The timing of pressure leaks is highly coincident with onset of cold-temperatures as can be seen in Figures 9 and 10. The hydrographs for Pelly, Nisling and Tatshenshini Rivers (Figure 9) all show a rapid drop in water level of about 1.5 to 2 m that occurs during the first cold snap of the year.

The hydrographs for Old Crow, Yukon and Liard Rivers (Figure 10) all show a rapid drop in water level of a similar magnitude during the second major cold snap in late January. The magnitude of the apparent decrease in water level is a function of the head above the orifice at the time of the leak. The post-leakage record varies in characteristics from station to station. A straight-line is expected (e.g. Old Crow) if the leakage is consistently open to the atmosphere. Variation in the record is a function of the efficiency of the leak.

4.0 Discussion

There are many sources of uncertainty in the interpretation of water level records during the winter season. The dynamics of ice accumulation and release processes can be highly irregular causing substantial and unpredictable water level fluctuations. The monitoring technology most commonly used to record continuous water level records is prone to cold-temperature failure for a number of reasons producing data that can be difficult to discriminate from ice-effects. There may be little, or no, direct relation between stage and discharge throughout much of the winter resulting in invalid discharge estimates even when the water level data is valid. Validity, for the purpose of this discussion, is defined as data that are reasonably likely to be representative of reality and does not imply accuracy at any given level of precision. Table 3 lists statistics of the data reliability for the 11 stations investigated for the eight-month period from October 1, 2001 to May 31, 2002. The best case in this sample was the Klondike River station for which 100% of the water level data was valid and 64 days or 26% of the discharge data was valid. The worst case was Giltana Creek, which is a stilling well station for which only 11% of the data was valid for that eight-month period. Slightly more than half of the possible water level record for these stations is invalid because of temperature-related problems with the gauge.

Table 3. Real-time data reliability for the period October 1, 2001 to May 31, 2002

Station	Name	Valid water level	Valid discharge
09AB001	Alsek River above Bate Creek	100%	19%
09DB001	Beaver River below Matson Creek	35%	20%
08AA009	Giltana Creek near the mouth	11%	11%
09EA003	Klondike River above Bonanza Creek	100%	26%
10AA001	Liard River at upper crossing	66%	22%
09CA006	Nisling River below Onion Creek	33%	14%
09FC001	Old Crow River near the mouth	50%	5%
09BC001	Pelly River at Pelly Crossing	40%	20%
09DD003	Stewart River near the mouth	62%	11%
08AC002	Tatshenshini River near Dalton Post	24%	23%
09CD001	Yukon River above White River	56%	17%
	Average	**48%**	**16%**

This sample of Yukon stations for one winter does not provide a complete list of the water level and discharge pathologies that plague winter hydrometric operations. Winter monitoring difficulties provide us with only a very limited set of valid water level data that can be explored to learn about the effects of ice on water level. Because the symptoms of many ice effects are quite similar to equipment failure symptoms, correct interpretation of winter hydrometric data requires a good knowledge of river ice processes and dynamics as well as a good understanding of the equipment used to collect the data.

The most commonly occurring cold weather technical problem is pressure loss from gas purge pressure transducer systems. However there are many other problems that may occur throughout the winter that may also result in the mis-interpretation of water level data. Some of the most troubling problems include: orifice movements due to ice scour, frozen orifices, blockages in the pressure system (ice formation at low points in the line), power supply problems resulting from snow accumulation on solar panels, and frozen stilling wells.

5.0 Conclusion

The publication of hydrometric data in real-time on the world-wide-web is now taken for granted in many countries. However, real-time data issues for winter hydrometry are more profound than the technological challenges of developing of a web site to display data obtained by telemetry. Discharge data computed from a stage-discharge relation will be invalid if the station is in ice-effect, and much of the water level may be invalid due to temperature related problems with the gauging equipment. Distinguishing between valid and invalid water level data can be difficult and generally requires extensive experience and a high degree of familiarity both with the technology in use and with river ice processes. The consequences of misinterpretation of the data could be quite high. A sudden drop in water level that could be interpreted as a pressure loss in gauging equipment, may actually be warning of massive storage of water behind an upstream ice jam creating a flood hazard for downstream communities, or vice-versa.

It is obvious that monitoring technologies are needed that will be more robust to the demands of winter operations. However, development and deployment of those technologies may take years to achieve once we become aware of a suitable solution. A system to automatically detect erroneous data and warn real-time data users of these problems could be an interim mitigation for this problem. Such a system would have to be able to distinguish between instrumentation problems and river-ice processes that can be symptomatically quite similar. The design of a system that can distinguish between such ambiguous signals would have to be based on a very good understanding of river-ice processes as well as a very good understanding of the full range of technological impairments. The WSC could follow the lead of the USGS and provide censoring of the real-time data by experienced technologists. This may be an effective interim mitigation, but will not be error-free because this additional duty would be compromised by existing operational schedules and priorities. Alternatively, the Water Survey can continue to publish real-time data, un-censored, as it is received but rely on the users of the site to use the data with discretion. This option presumes that end-users of the data are prepared to take some of the responsibility for data interpretation and that end-users have access to the necessary resources to learn about hydrograph diagnostic techniques. At a minimum, the actual field-survey measurement data should also be published on the web to provide invaluable calibration points for the end-user to evaluate.

It is unlikely that the WSC can solve the many and various problems of winter hydrometry before unfortunate decisions are made based on immediate access to erroneous data. This fear of negative consequences provides the basis for arguments against real-time data dissemination to the general public. However, this risk must be put in the perspective of the many positive aspects of real-time data dissemination. Exposing problems rather than hiding them will raise awareness of the issues of winter hydrometric operations and lead to a greater resolve to find solutions. The timing, magnitude and variability of winter water level fluctuations will become apparent to many users who have previously assumed that winter streamflow is relatively uneventful based on heavily censored and modified published streamflow estimates. Flood forecasting centres now have access to data that may be meaningful for ice-jam flood prediction and scrutiny of this data by knowledgeable experts will almost certainly lead to improvements in forecasting an important but often-neglected flood generation mechanism.

There are no simple answers, but timely access to imperfect data is probably better than no access for Canadian water resources management. The path forward to improved hydrometric data is to first identify and quantify these problems so that the scientific, engineering and technological communities can all contribute to the search for solutions.

6.0 References

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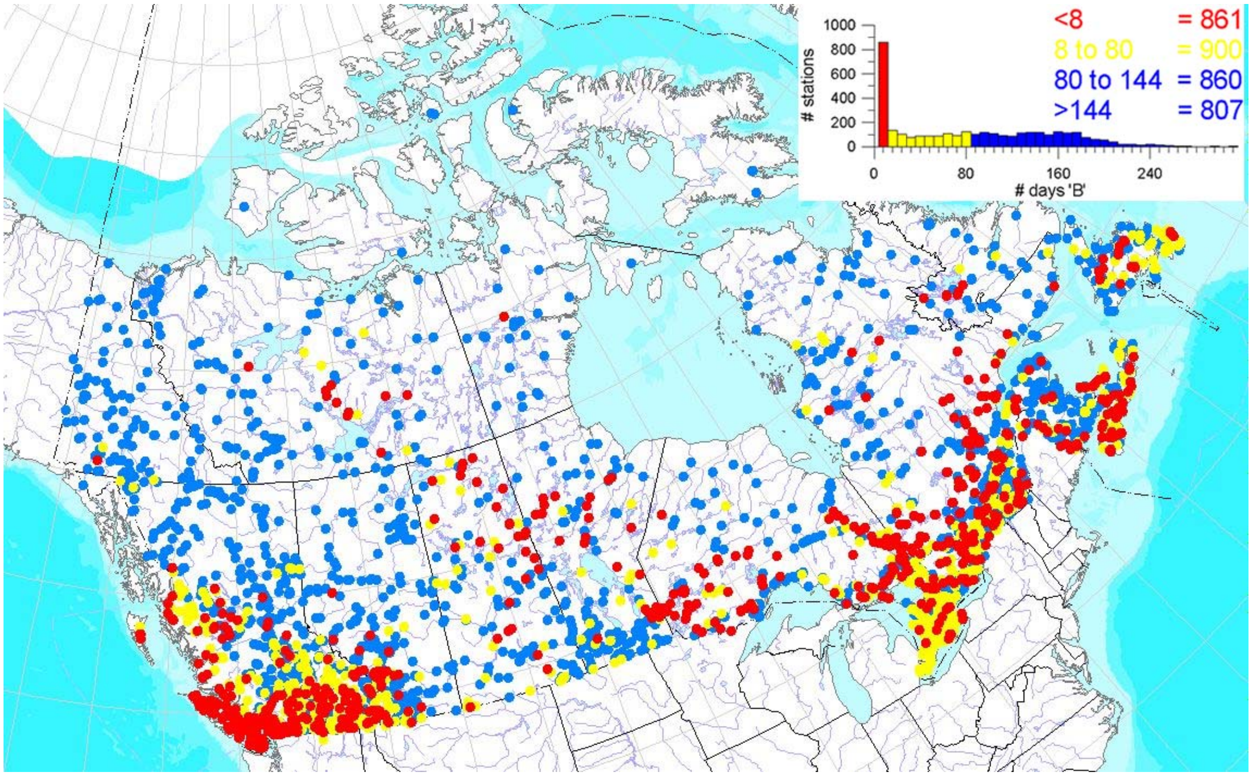

Figure 1. Map of Canada showing WSC hydrometric network, including active and discontinued stations, colour coded by length of ice cover. The histogram shows the frequency distribution of the stations by length of ice cover.

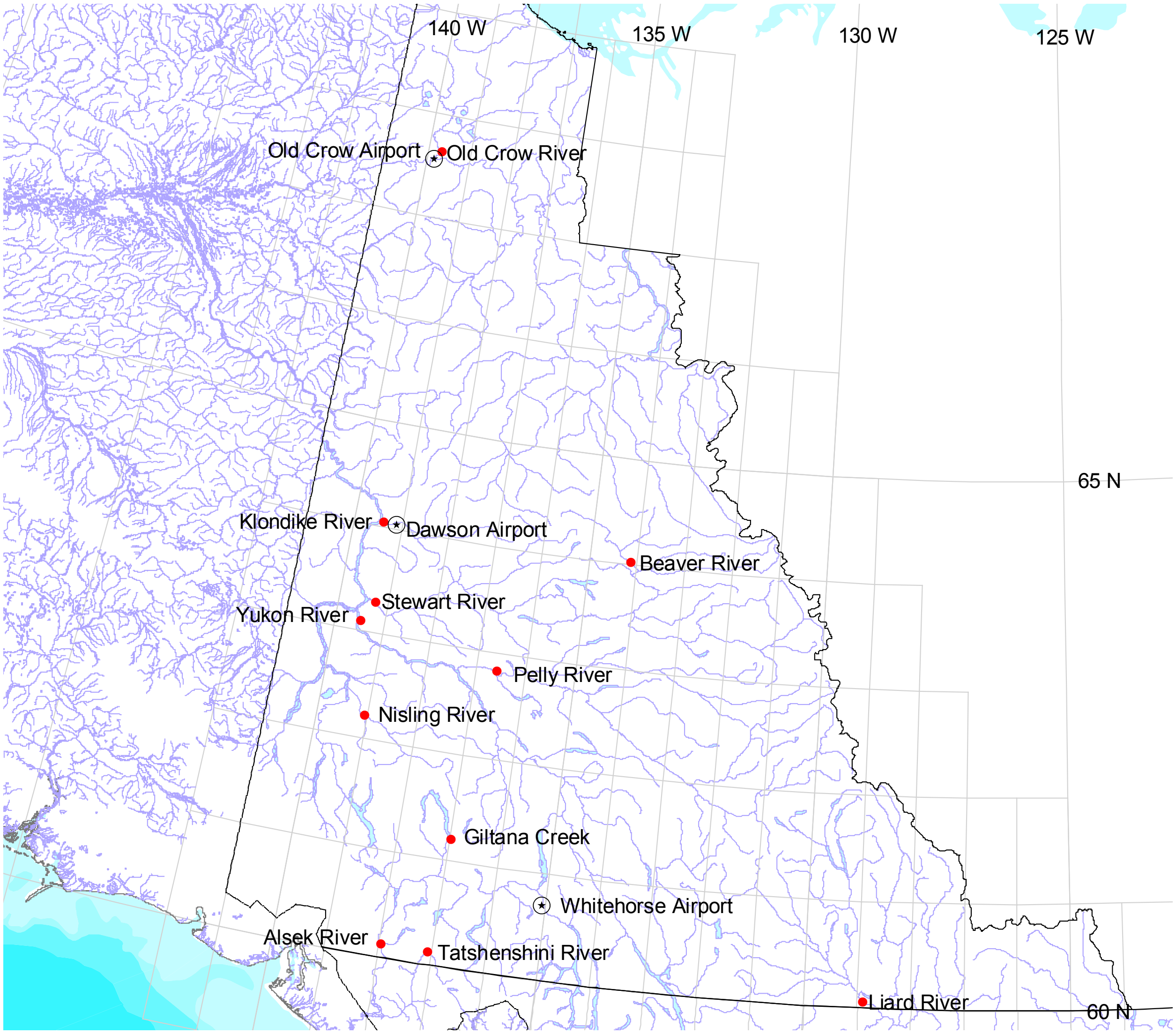

Figure 2: Map of the Yukon Territory showing the location of the real-time hydrometric network and the location of the climate stations used for comparative analysis.

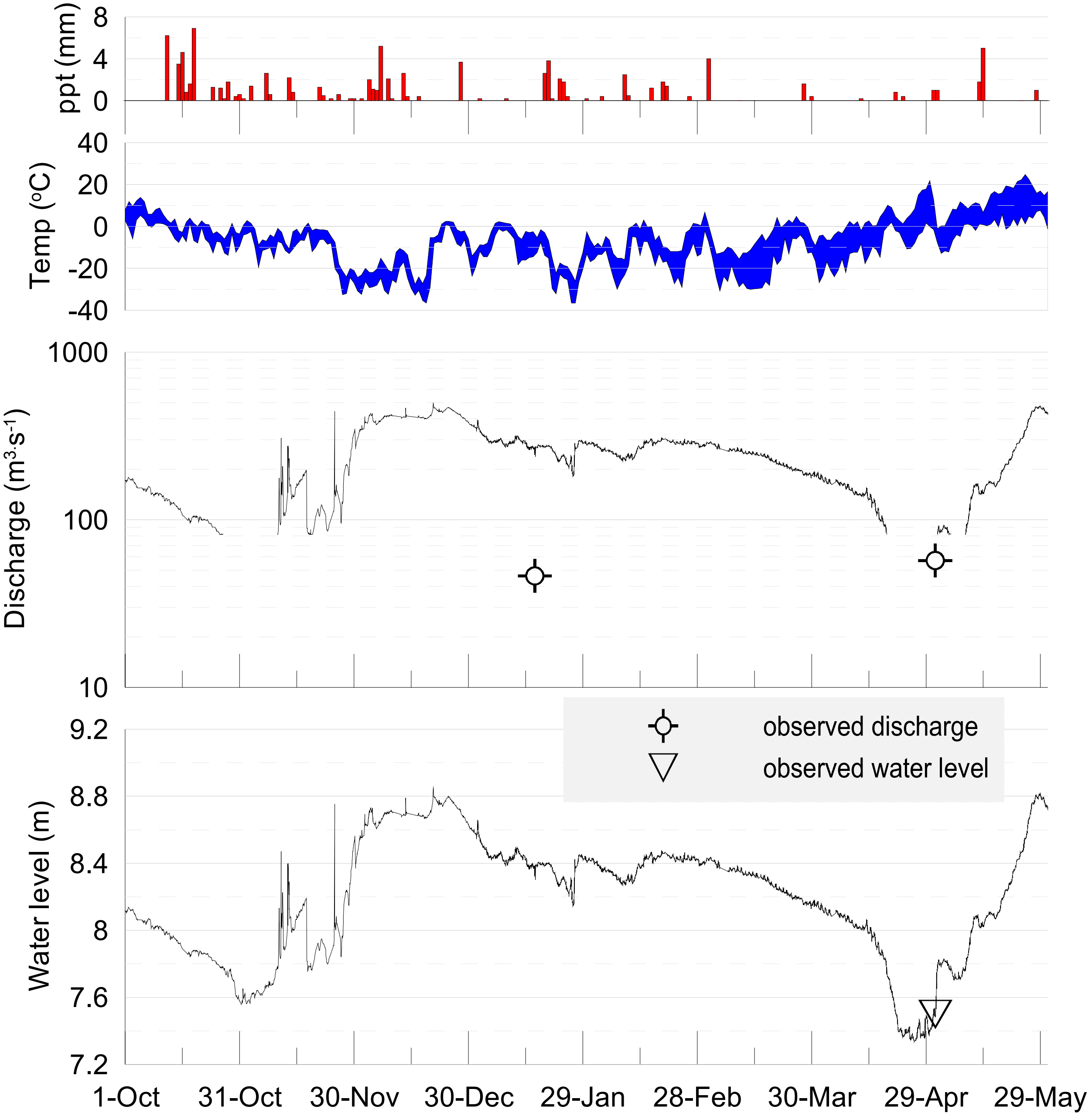

Figure 3. Whitehorse Airport precipitation and temperatures (maximum and minimum daily); Alsek River above Bates Creek discharge and water level data taken from the real-time web site (2001-2002); Field-survey (observed) data are added to provide context.

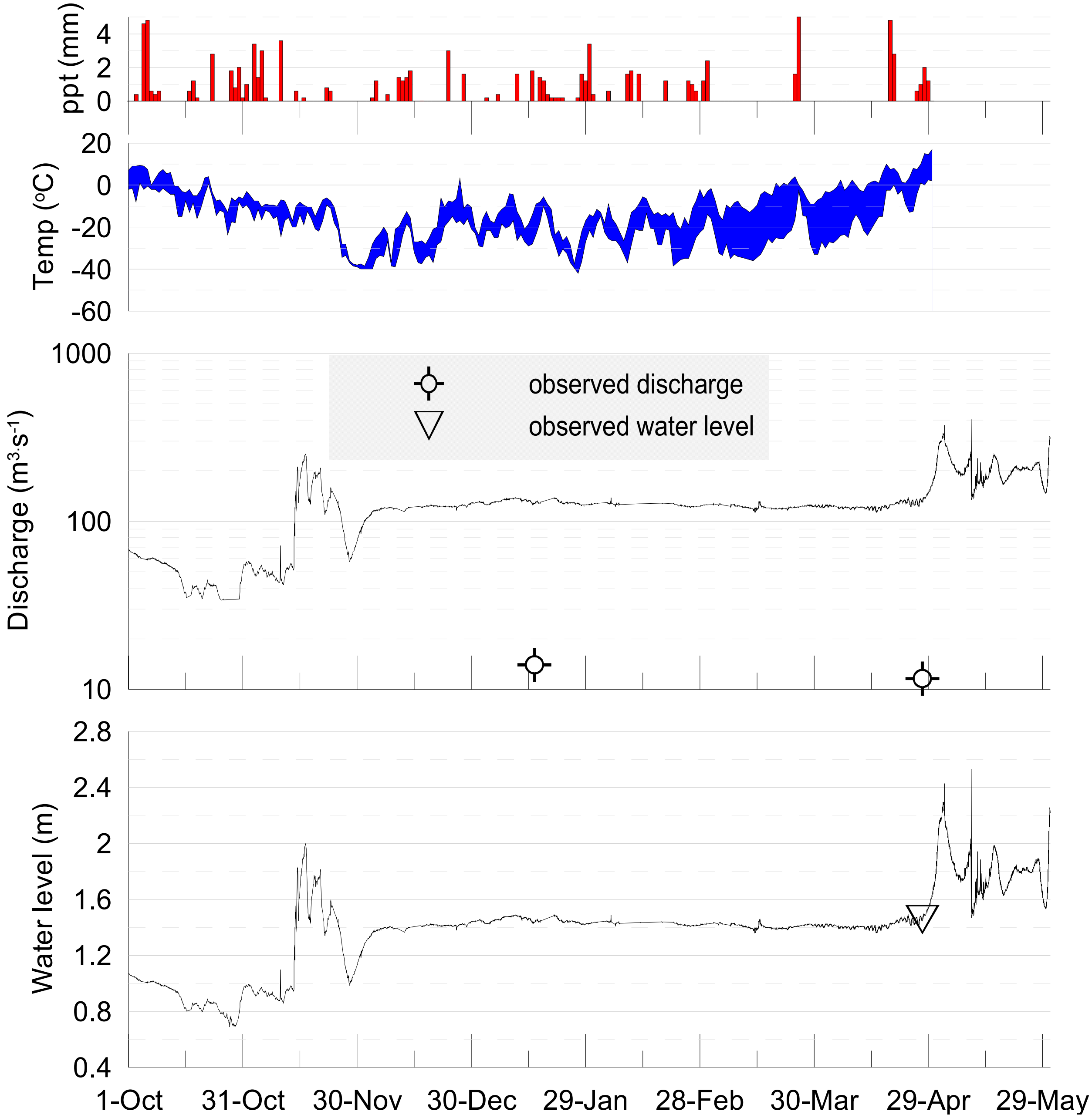

Figure 4. Dawson Airport precipitation and temperature (maximum and minimum daily); Klondike River above Bonanza Creek discharge and water level taken from the real-time web site (2001-2002); Field-survey (observed) data are added to provide context.

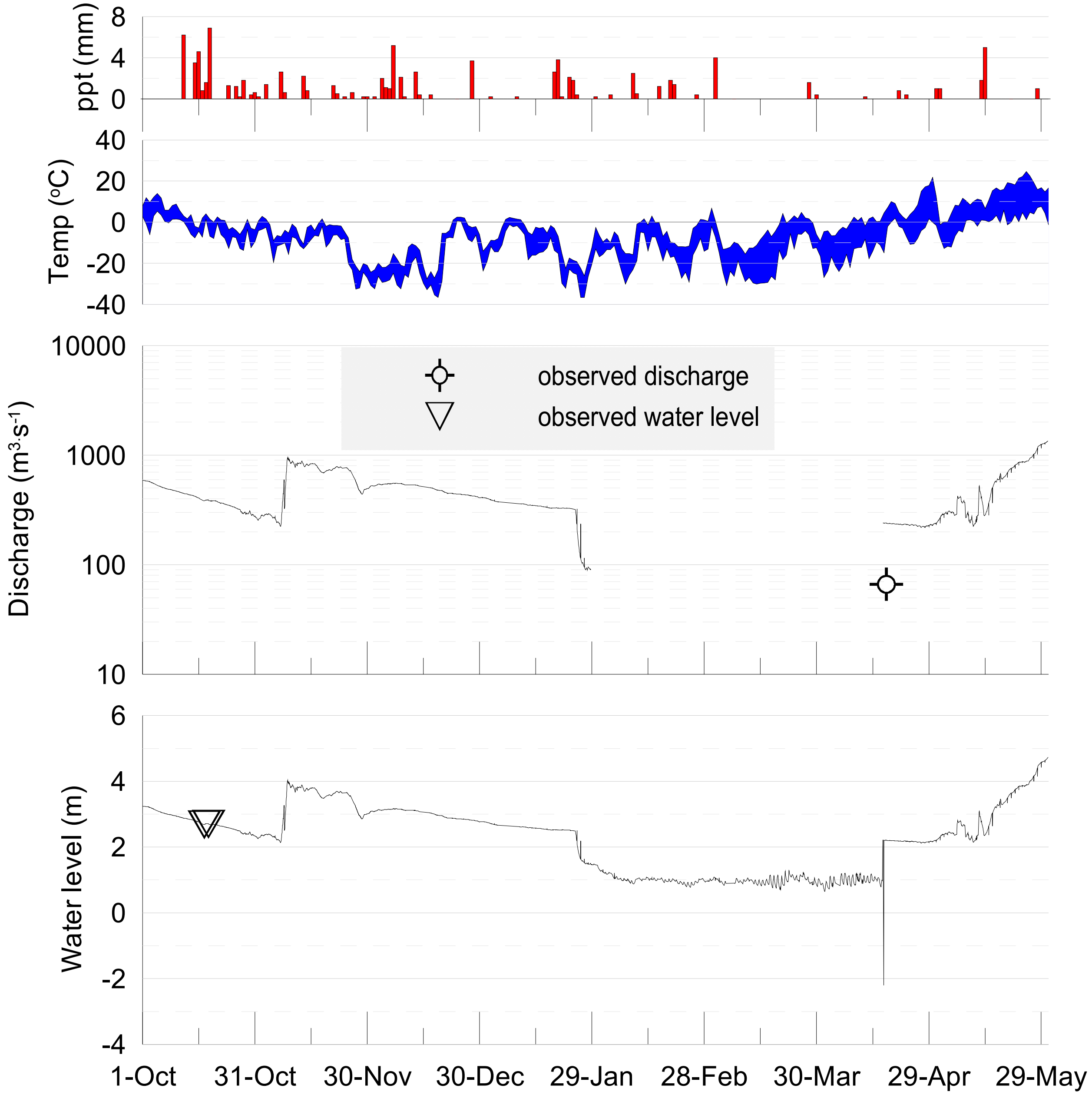

Figure 5. Whitehorse Airport precipitation and temperature (maximum and minimum daily); Liard River at upper crossing discharge and water level taken from the real-time web site (2001-2002); Field-survey (observed) data are added to provide context.

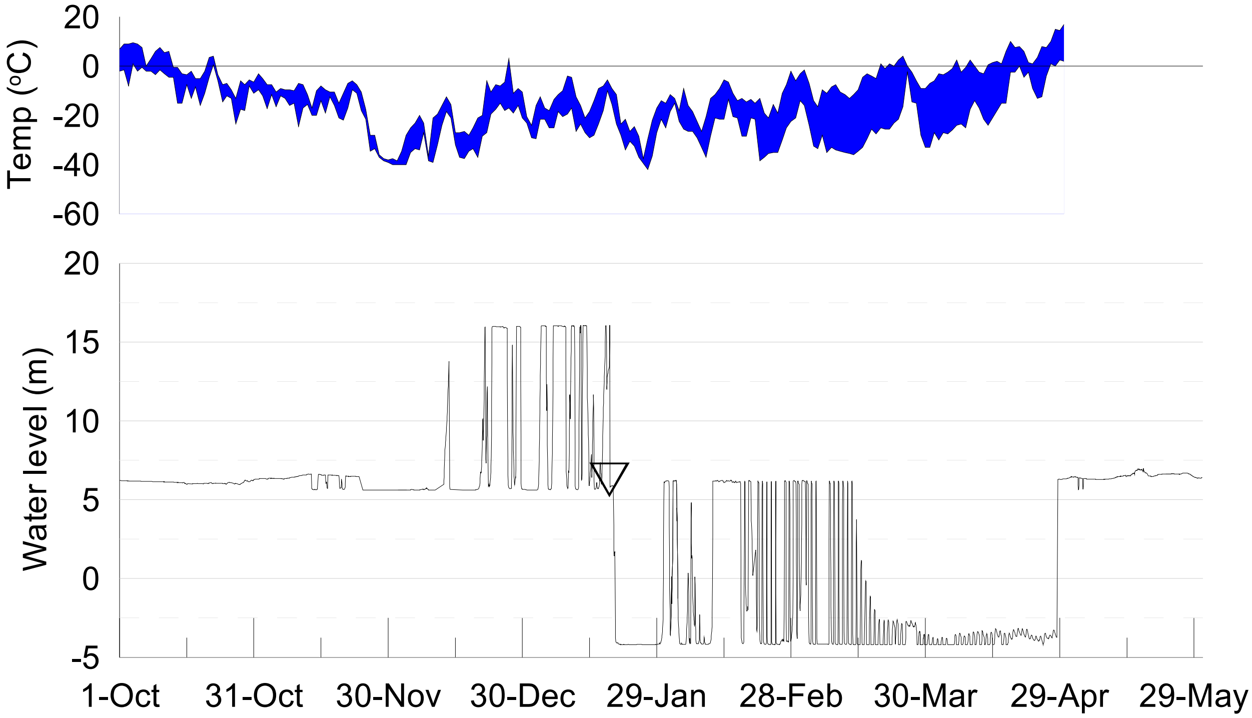

Figure 6. Dawson Airport temperature (maximum and minimum daily); Beaver River below Matson Creek water level taken from the real-time web site (2001-2002); Site visits are indicated with inverted triangles.

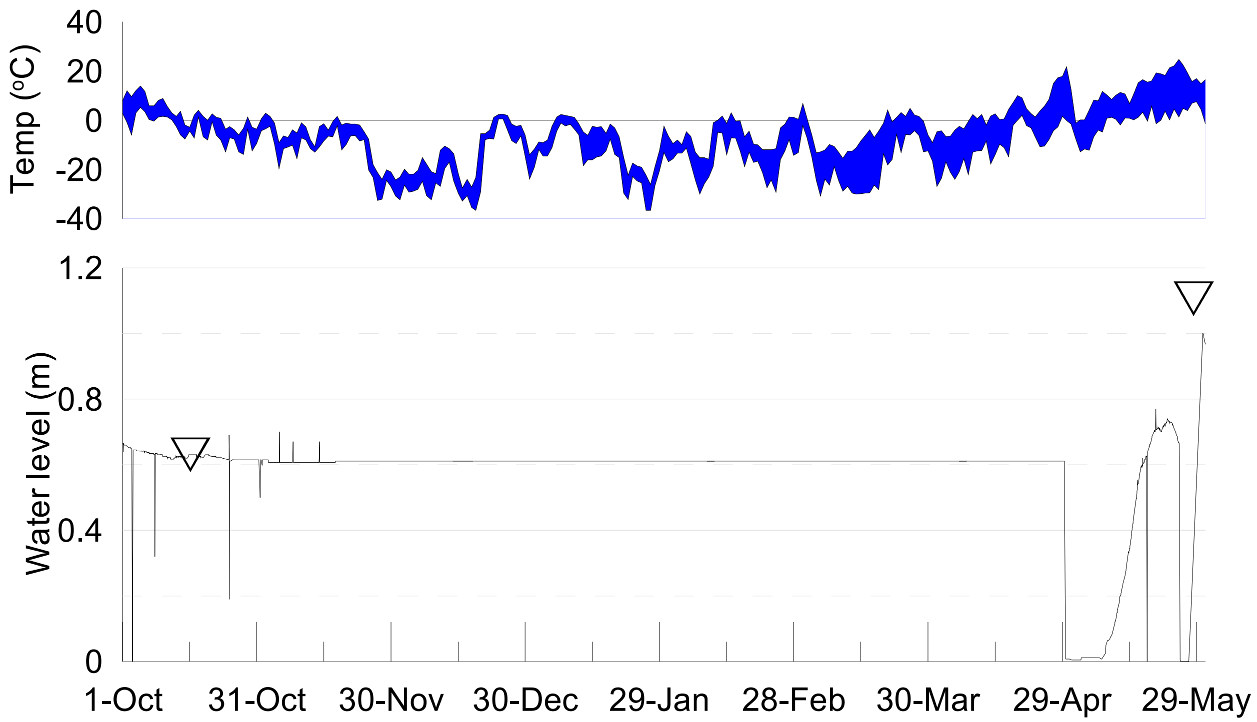

Figure 7. Whitehorse Airport temperature (maximum and minimum daily); Giltana Creek near the mouth water level data taken from real-time web site (2001-2002); Site visits are indicated with inverted triangles.

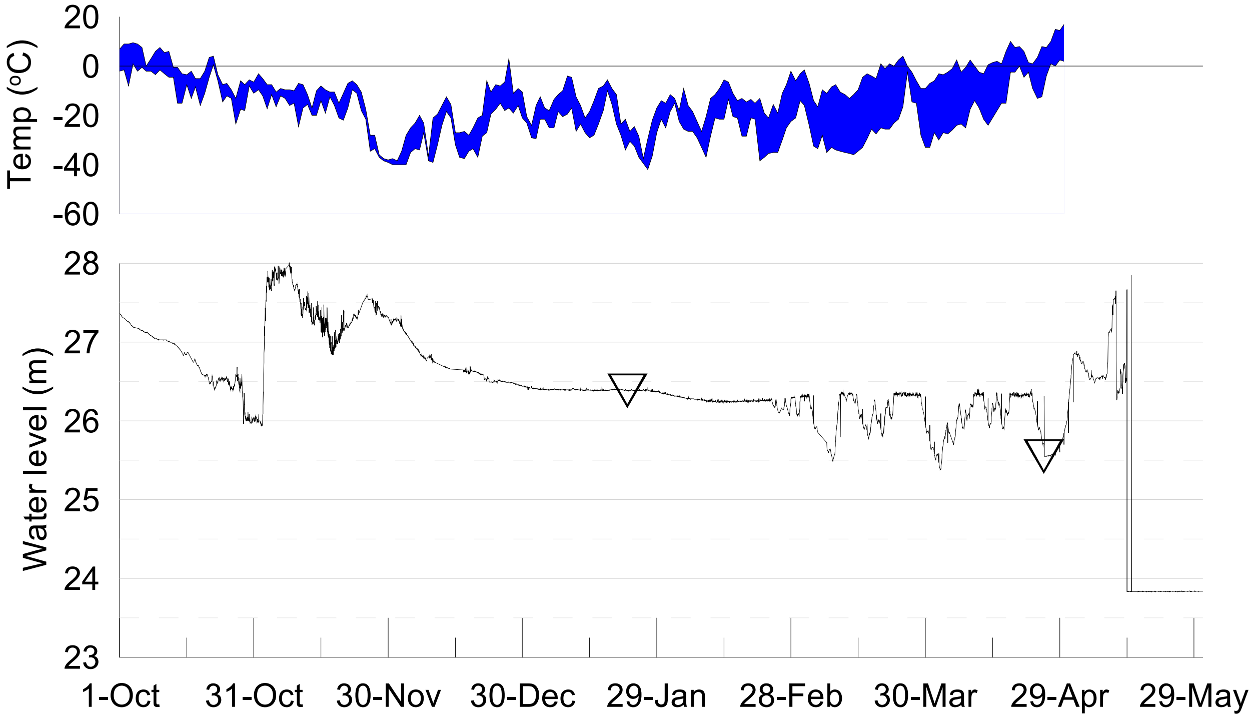

Figure 8. Dawson Airport temperature (maximum and minimum daily); Stewart River below Matson Creek water level taken from the real-time web site (2001-2002); Site visits are indicated with inverted triangles.

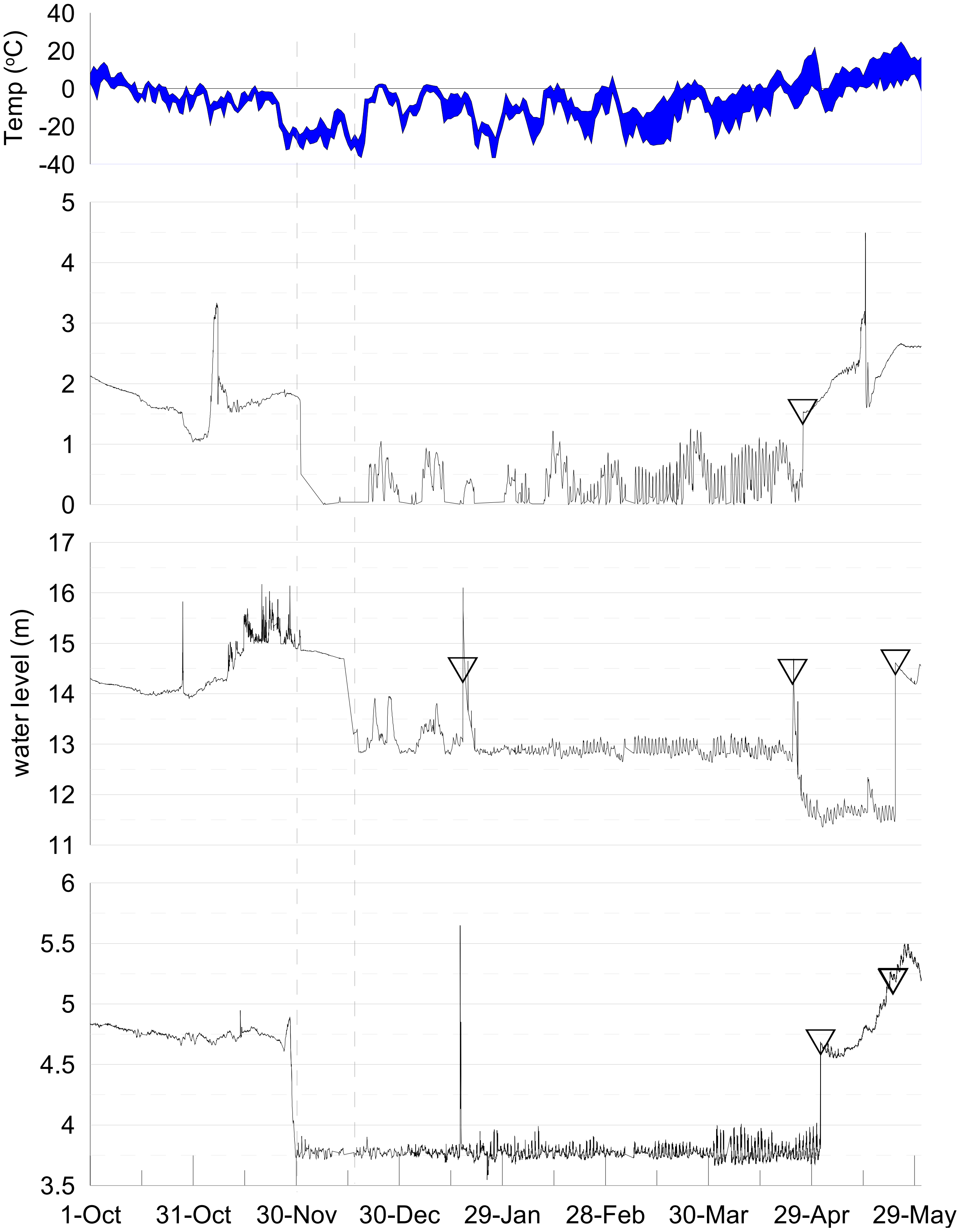

Figure 9. Early-winter event: Whitehorse Airport temperature (maximum and minimum daily); Pelly River at Pelly Crossing (2nd from top); Nisling River below Onion Creek (2nd from bottom); and Tatshenshini River near Dalton Post (bottom).

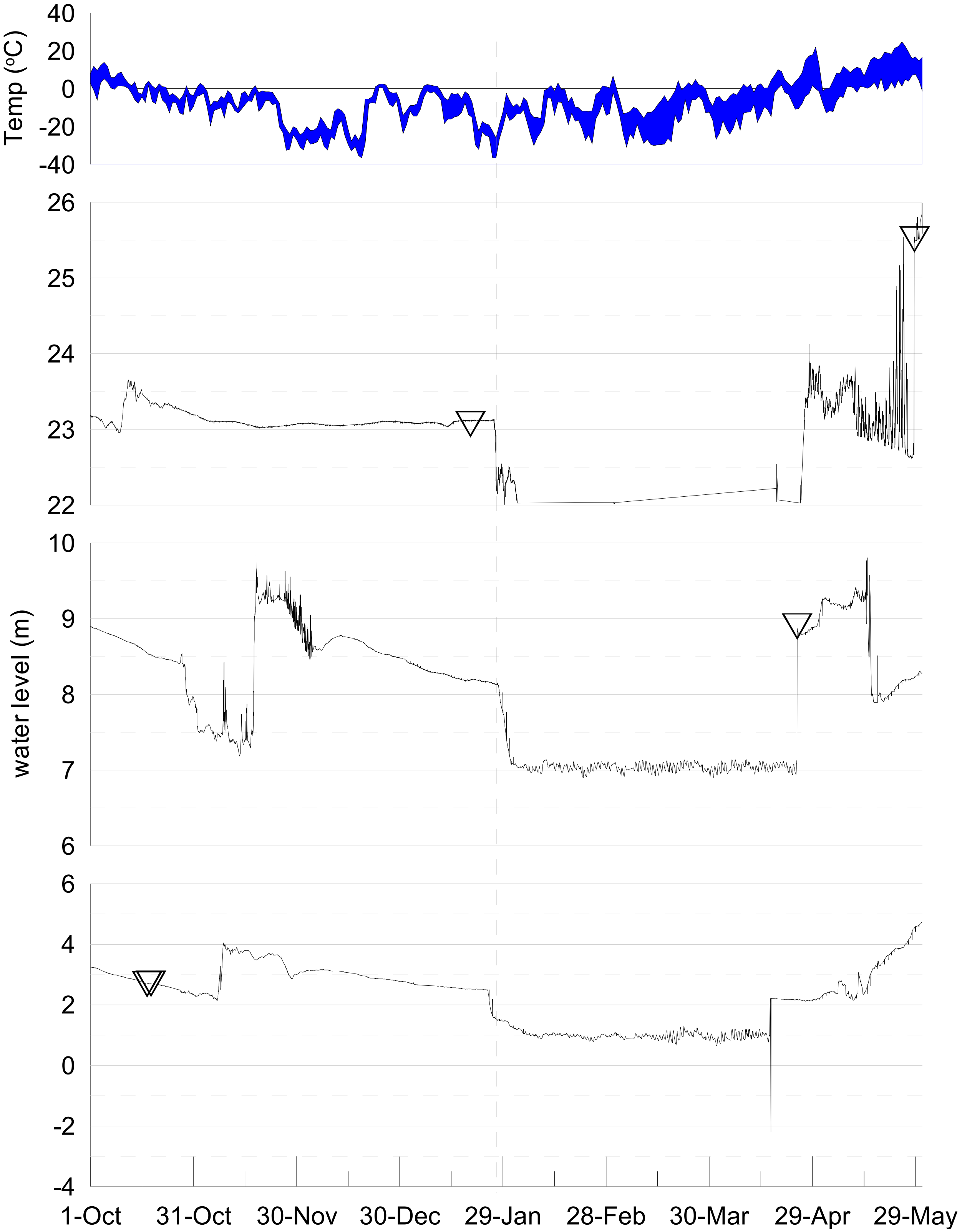

Figure 10. Mid-winter event – Whitehorse Airport temperature (maximum and minimum daily); Old Crow River near the mouth (2nd from top); Yukon River above White River (2nd from bottom) and Liard River at upper crossing (bottom.