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Estimation of Channel Discharges under Complete Ice Cover

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Most Canadian rivers are affected by the ice conditions during winters. Presence of ice cover significantly alters the channel hydraulics such that the open flow stage-discharge relationship not applicable for flow under ice cover. Determination of channel discharges under ice cover is a challenge to operations of water resource agencies. Daily discharge measurements would be ideal for producing winter flow data, however, the constraints on operational budgets make it impractical.

Faced with this challenge, a project of winter discharge estimation is conducted at WSB to develop a systematic procedure for estimating winter discharges with data available at a channel gauging station. This procedure aims at producing real-time winter discharge estimates using channel stage and air temperature data, as well as analytical results of historical winter flow measurements at the site.

Basic propositions built in the procedure include:

- the thickness of ice cover over the winter is estimated with the values of accumulative-freezing-degree-day at the site via the Stephan's Equation;
- the elevation of ice cover bottom is more indicative than channel stage for estimating winter discharges, and its value is approximated as the difference of channel stage and ice thickness;
- for flows under complete ice cover, there exists a relationship between the cross-section mean velocity and the elevation of ice cover bottom over the entire winter, and the relationship varies among different winters.

The procedure is successively tested for winter discharge estimation at more than ten hydrometric stations across Canada. In the winter of 2010/2011, this procedure is used for real-time winter discharge estimation at three WSB stations in Alberta. The procedure and the results of real-time winter discharge estimation are presented in this paper.

1. Introduction

The Water Survey Branch (WSB) of Environment Canada is in charge of collection and dissemination of channel discharge data for rivers across the country as a part of its mandate. Most Canadian rivers are affected by ice conditions during winters, which could be as long as six months in North. Discharges of natural channels under open flow conditions are commonly estimated with the observed channel stage records through the rating curve, the stage-discharge relationship established with measured stage and discharge data for the specific channel cross-section. Presence of ice cover significantly alters the channel hydraulics such that the open flow stage-discharge relationship not applicable for flow under ice cover.

Determination of channel discharges under ice cover is a challenge to operations of water resource agencies. At present, the only accurate means of determining winter discharges is by direct measurement. Ideally, frequent direct measurements are preferable throughout a winter season. However, the constraints on operational budgets make it impractical. As a routine of WSB operations, two or three flow measurements would normally be taken at a gauging station per winter (Moore *et al.* 2002). For the extended periods between direct measurements, channel discharges are typically estimated with conceptual and/or statistical interpretation of the measured data (Hamilton *et al.* 2001). Daily discharge data over winters are produced after the winter season passed, normally one year later. With this practice, near-real-time discharge estimation is impossible and a high degree of uncertainty should be expected with the produced winter discharge data.

Faced with this challenge, a project is conducted at WSB to develop a systematic procedure for estimating winter discharges with data currently available at a channel gauging station, which include the sparely-timed historical winter flow measurement records and continuously monitored hydrometric and climate parameters (i.e., channel stage and air temperature). This procedure aims at producing near-real-time (only with a time delay of a couple of days) winter discharge estimates using channel stage and air temperature data, as well as analytical results of historical winter flow measurements at the site.

The procedure is successively tested for winter discharge estimation at more than ten hydrometric stations across Canada. In the winter of 2010/2011, this procedure is used for real-time winter discharge estimation at three WSB stations in Alberta. The methodologies applied in the procedure are presented. The implementation of near-real-time winter discharge estimation is illustrated with examples and the results are compared with measured discharge values.

2. Methodologies and Data Requirement

The winter discharge estimation procedure involves the following quantities:

- AFDD: accumulated freezing-degree-day at the station;
- HG: channel stage at the station;
- WSIB: distance from water surface to the bottom of ice cover;
- IceT: average thickness of ice cover, used as approximate of WSIB;
- HIB: height of bottom surface of ice cover;
- Area: flow area at a channel cross-section;

- Vmean: cross-section mean velocity;
- Q: channel discharge.

The procedure accepts some simplifications and approximations:

- a standard cross-section is defined for the station, and data of historical flow measurements taken at various cross-sections of the station are assumed transportable to the standard cross-section;
- WSIB at the standard cross-section is approximated with the average value of measured values of IceT at sampling verticals across the cross-section.

This procedure uses data already available from on-going hydrometric and climate operations, including:

- bathymetry data at the standard cross-section of the station;
- open flow rating table of the station;
- daily mean stage data at the station (real-time data available at many WSB stations);
- daily mean air temperature at the station or at nearby MSC station (near-real-time data available);
- historical winter discharge measurement data at the station (normally two or three flow measurements taken per winter, including stage, discharge, ice thickness, slush, and etc.).

This procedure is developed with four basic propositions built on experience with flows under complete ice cover:

- IceT at the standard cross-section over the winter could be estimated by a relationship with the AFDD at the site;
- HIB is more indicative than HG for estimating winter discharges, and its value given as:

  $$HIB = HG - IceT \qquad [1]$$

- under complete ice cover, a certain relationship between Vmean and HIB exists for a winter, and the relationship varies with different winters;
- the freezing-up conditions of the channel, i.e., the discharge value and the HIB value at the date when complete ice cover first formed, possesses dominate influence on the channel hydraulics over the entire winter.

2.1 Estimating values of IceT with AFDD Values

The thickness of ice cover over the winter could be estimated with the values of accumulative-freezing-degree-day (AFDD) at the site via the Stephan's Equation, established with regression analysis of historical measurement data of IceT and AFDD.

$$IceT = b_0 + b_1 \times \sqrt{(AFDD)} \qquad [2]$$

where b_0 and b_1 are regression coefficients, and √ for square root function.

An example of estimation of IceT by AFDD is shown with the following graph.

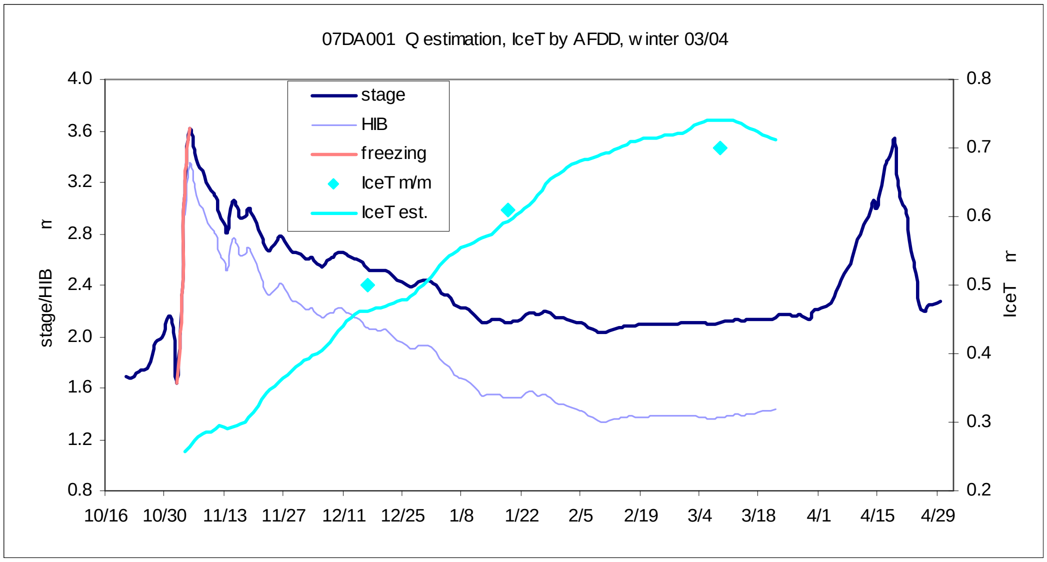

Figure 1. Estimated values of IceT, 07DA001, winter 2003/2004

2.2 Identifying the freezing-up period and estimating freezing discharge value

The complete ice cover of a channel would be formed in a period of a couple of days to a few weeks, depending on the climate and hydraulic conditions at the site. The channel freezing-up period was identified by examining two factors: the air temperature condition and the sharp change in channel stage. An example of the identification process, for the WSB station 07DA001, is shown here, which is consistent with observations of on-site video monitoring device of University of Alberta.

The freezing-up conditions of the channel, i.e., the discharge value and the HIB value at the date when complete ice cover first formed, possesses dominate influence on the channel hydraulics over the entire winter. However, measured value of the freezing-up discharge is normally unavailable. The freezing discharge needs to be estimated first. For rivers in the Prairie, there is usually a prolonged dry season prior to the winter, the freezing discharge can be estimated with baseflow recession of open flows over the prior dry season to the identified freezing date, as shown in the following graph. However, for rivers in Eastern Canada, there are normally significant runoff events prior to freezing-up and the freezing discharge can be estimated with flow recession over the pre-freezing period.

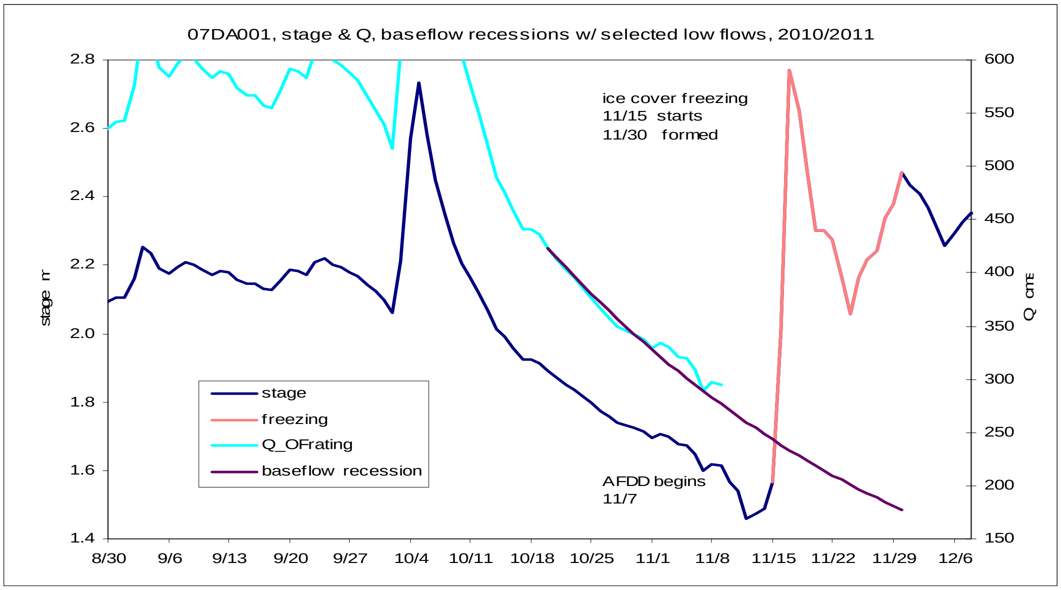

Figure 2. Identifying freezing period and freezing discharge, 07DA001, winter 2003/2004

2.3 Establishing Vmean vs. HIB relationship with historical flow measurement records

Well-defined Vmean–HG relationships exist for open channel flows, and can be specified based on open flow rating curves. But a unique Vmean–HIB relationship does not exist for flows under ice cover at a hydrometric station, as illustrated with next graph, where Vmean–HIB data points collected with seventeen discharge measurements over six winters from 2001 to 2007 are plotted.

However, a reasonably defined Vmean–HIB relationship is observed for data of an individual winter, as shown with the brown triangles on Figure 3. This observation, as well as that at many other stations, leads to the propositions that consist of the backbone for the winter discharge estimating procedures:

- a corresponding relationship of Vmean vs. HIB for flow under complete ice cover exists for each individual winter at a station;
- the relationship can be established with measured Vmean and HIB values, and a linear regression equation can be used to represent this relationship;
- the relationship varies in successive winters;

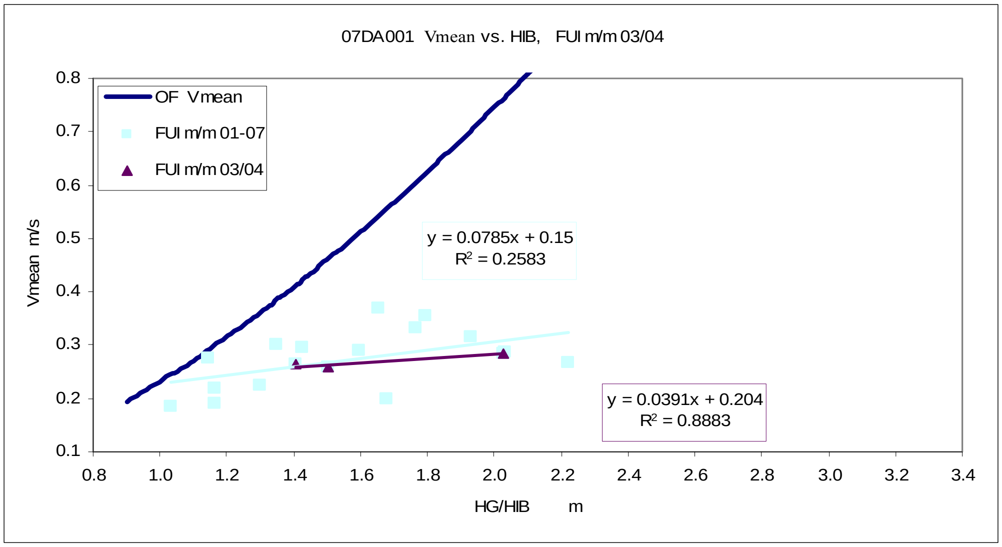

Figure 3. Vmean vs. HIB, from measurement data, 07DA001, winter 2003/2004

It is noticed that winter discharge measurements are normally taken in the middle of winter with lower values of HIB due to lower stage and thicker ice cover. During the early dates of ice-covered period, the HIB values are higher. This necessitates to extend the Vmean–HIB relationship to higher HIB values. Observations on flows under ice cover also indicate that the ice cover freezing-up conditions of a winter affect the channel hydraulics over the entire ice-covered period, including the Vmean–HIB relationship. The ice cover freezing-up conditions of a winter should be represented in the Vmean–HIB relationship, and the Vmean–HIB relationship for a winter should be established with the measured discharge and HIB data together with the discharge and HIB values on the date when the complete ice cover first forms. An example of the extended Vmean–HIB relationship for a winter is illustrated with the following graph.

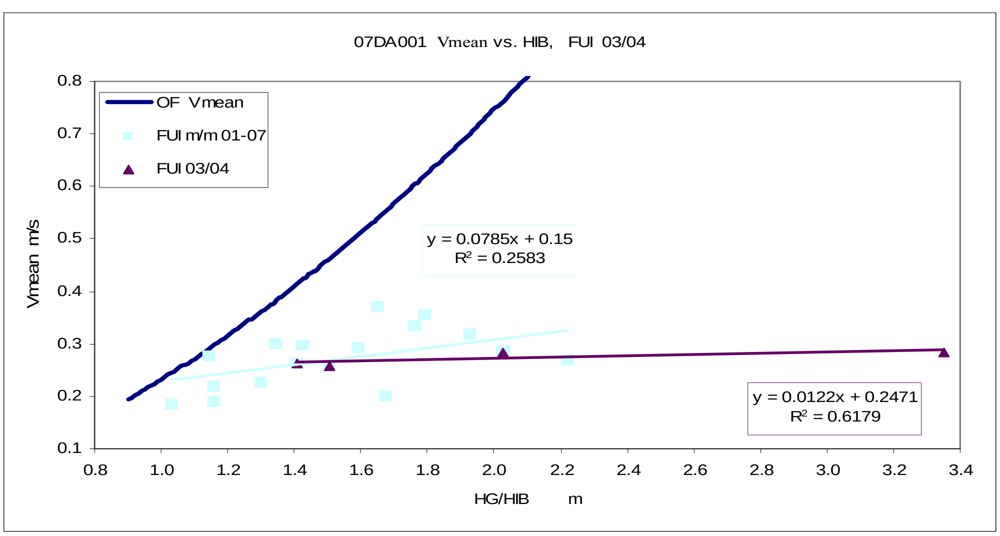

Figure 4. Vmean vs. HIB, w/ m/m data & freezing analysis, 07DA001, winter 03/04

A linear regression equation is used to represent this relationship as:

$$\text{Vmean} = b_0 + b_1 \times \text{HIB} \qquad \text{where } b_0 \text{ and } b_1 \text{ are regression coefficients.} \qquad [3]$$

The Vmean–HIB relationships of flows under ice cover for successive winters at a station can be established. An example for the WSB station 07DA001 over the winters 2001-2007 is summarized on Figure 5.

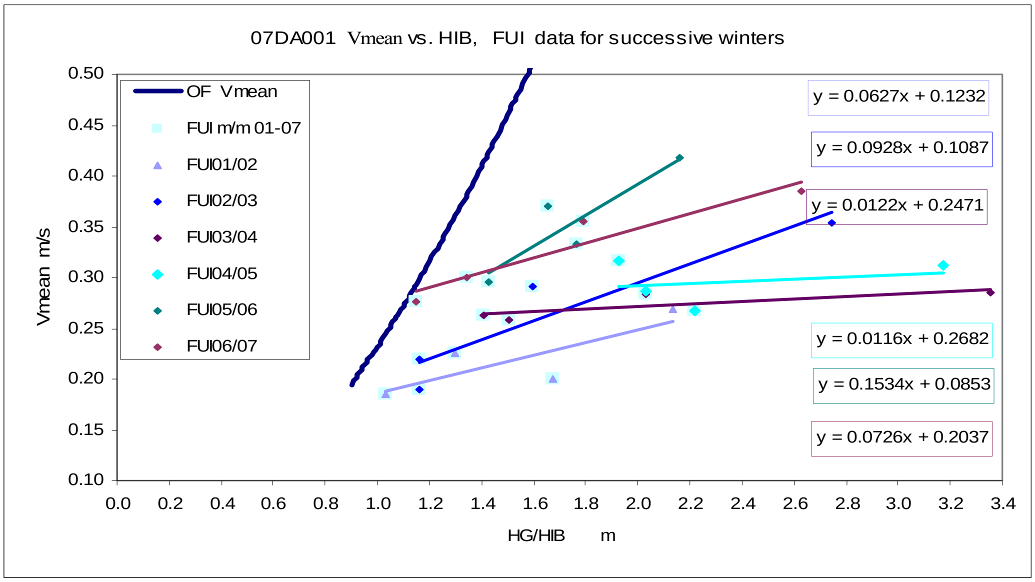

Figure 5. Vmean vs. HIB, with m/m data & freezing analysis, 07DA001

2.4 Establishing real-time Vmean vs. HIB relationship for the current winter

To accommodate near-real-time winter discharge estimation, the regression equation of the Vmean-HIB relationship for the current winter needs to be established before the flow measurement data for this winter get available. This is implemented with the results of ice cover freezing-up analysis for the current winter together with the established Vmean-HIB relationships for the previous winters at the same site.

It is observed on Figure 5 that the regression lines representing the Vmean-HIB relationships for the successive winters are concentrated in a belt on the Vmean-HIB space. This is also observed for other stations. Based on these observations, it is assumed that all these lines converge to a point at the far end on the space, and the coordinate of the converging point is approximated as the average value of the intercepts of the regression equations representing the Vmean-HIB relations for successive winters.

With the converging point specified with the Vmean-HIB relationships of previous winters and with the Vmean-HIB value pair representing the freezing discharge Q_i for the current winter as identified, the real-time Vmean-HIB relation for the current winter can be defined. This feature makes real-time discharge estimation possible. An example of the derived real-time Vmean-HIB relation for the current winter is illustrated with the following graph.

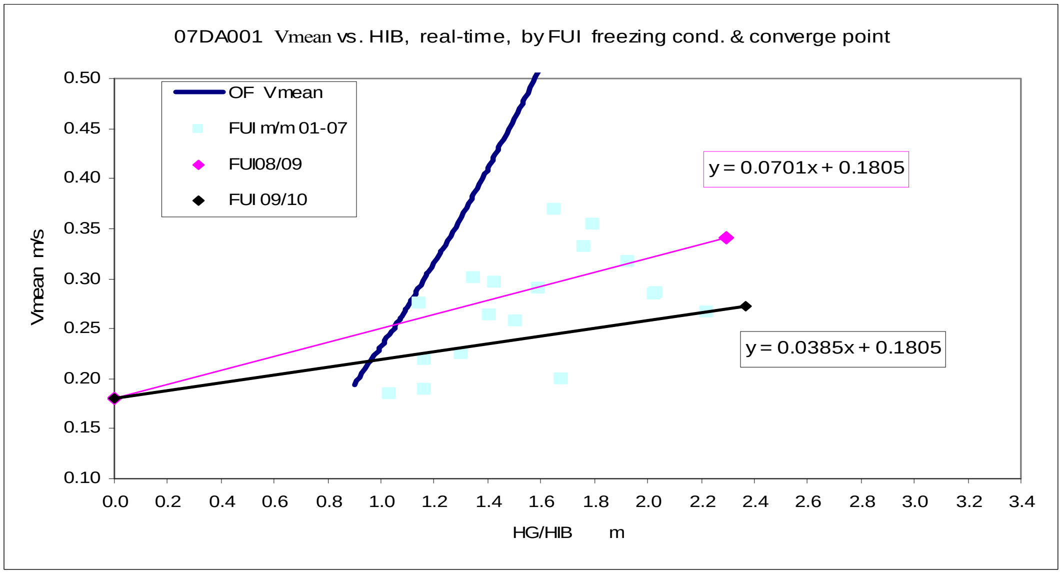

Figure 6. Real-Time Vmean-HIB Relationship, 07DA001, winters 08/09 & 09/10

2.5 Calculation of winter discharge estimates for the current winter

With the IceT values estimated, the HIB values can be specified. With the established real-time regression equation of Vmean–HIB for the current winter, values of Vmean can be calculated with the respective values of HIB. The flow area (Area) of the standard cross-section with respect to the corresponding value of HIB is calculated with the bathymetry data at the standard cross-section. The channel discharge is then computed as the product of Vmean and Area.

$$Q = \text{Vmean} \times \text{Area} \qquad [4]$$

3. Near-Real-Time Winter Discharge Estimation for Three WSB Stations

This procedure was used for near-real-time winter discharge estimation for three WSB stations in Alberta over the winter 2009-2010 and the winter 2010-2011, the Athabasca River (WSB Station 07DA001), the Smoky River (WSB Station 07GJ001), and the Clearwater River (WSB Station 07CD001). Discharge measurement data for the current winter are only used for comparison purposes.

The air temperature data are obtained at the MSC web sites, and the channel stage data are from WSB web sites with real-time stage monitoring devices. The real-time Vmean-HIB regression relationships are established with historical data via the procedure presented in this reports. The values of Vmean can be estimated with the derived real-time Vmean-HIB relationship. As time goes on, discharge measurement data gets available, and used as verification of the discharge estimation. Results of near-real-time winter discharge estimation are presented separately for the three WSB Alberta stations in the following hydrographs.

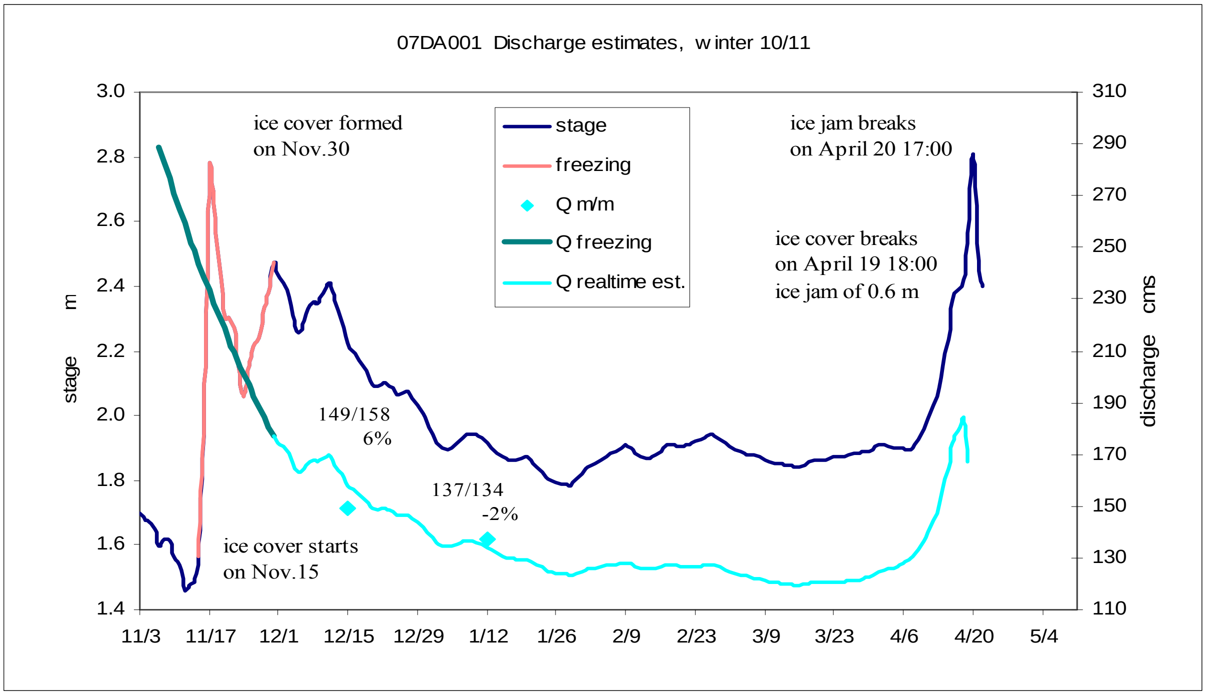

Figure 7. Results of near-real-time discharge estimation, 07DA001 winter 2010/2011

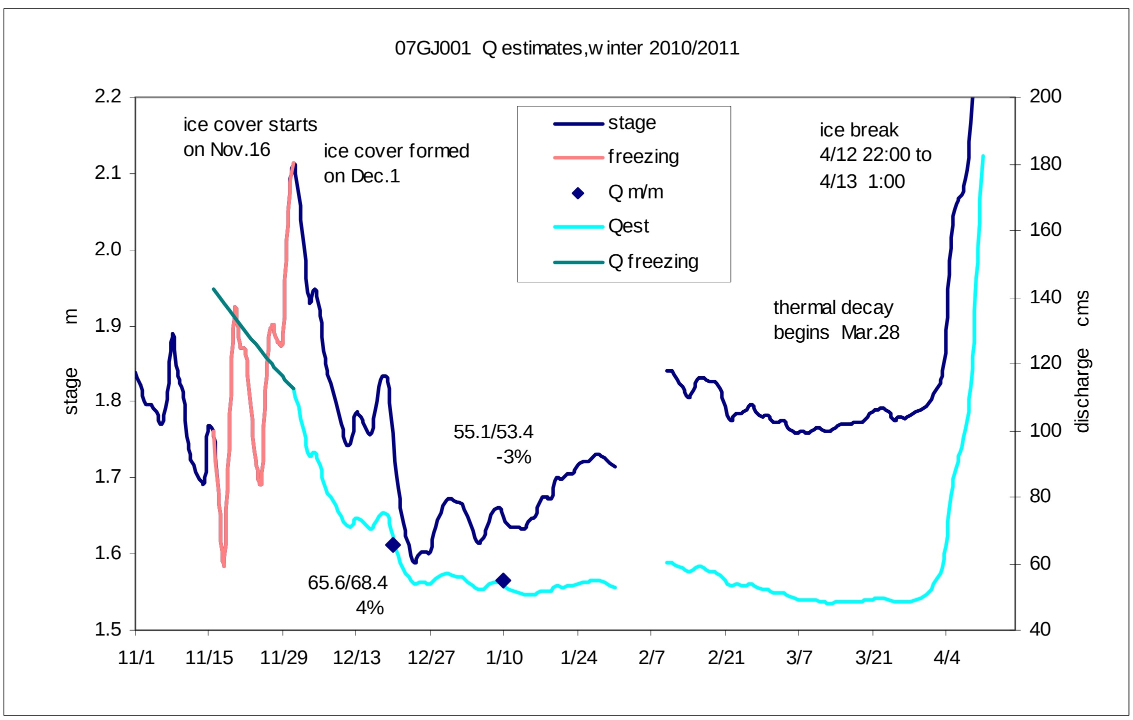

Figure 8. Results of near-real-time discharge estimation, 07GJ001 winter 2010/2011

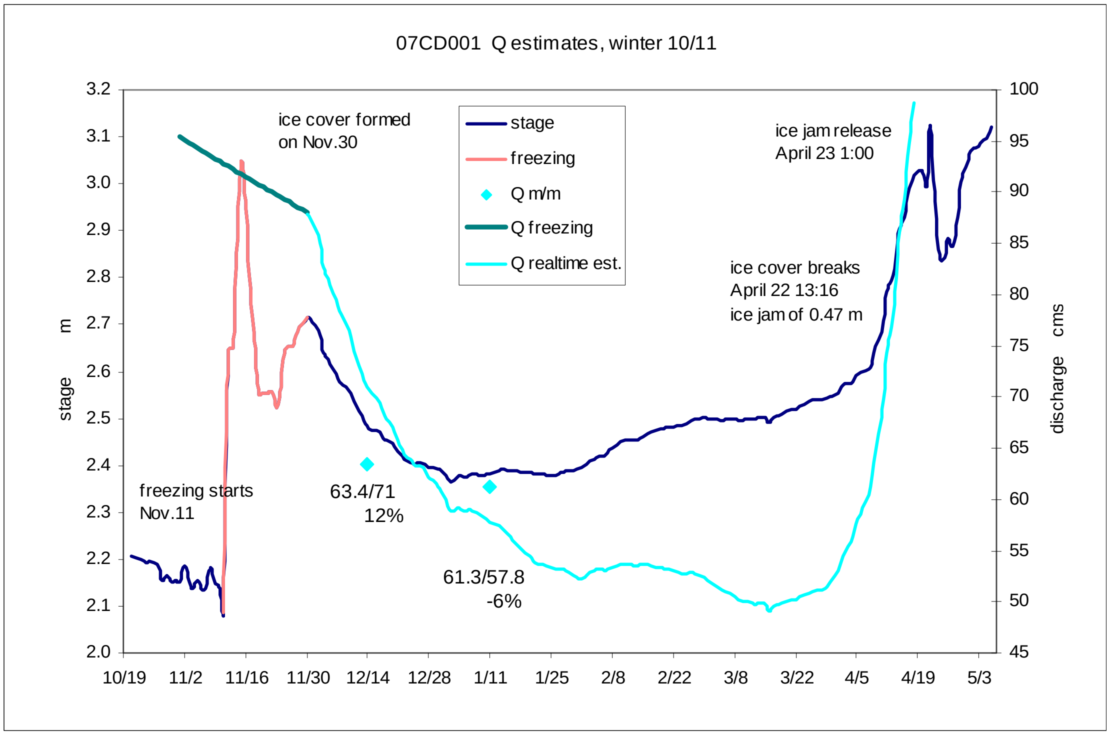

Figure 9. Results of near-real-time discharge estimation, 07CD001 winter 2010/2011

4. Summary

The systematic procedure for estimating winter discharges with data currently available at a channel gauging station was developed at WSB. The procedure is capable of producing near-real-time (only with a time delay of a couple of days) winter discharge estimates. The data requirement for applying the procedure includes the sparely-timed historical winter flow measurement records and continuously monitored hydrometric and climate parameters (i.e., channel stage and air temperature).

When the flow discharge measurement data of the current winter get available as time goes on, the equations used for discharge estimating can be modified accordingly. That is, this procedure can also be used for discharge data production for the winter with flow measurement data available.

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