Estimation of Winter Streamflow Using a Conceptual Hydrological Model: A Case Study, Wolf Creek, Yukon Territory.

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Abstract:

The objective of the Estimation of Discharge Under Ice Project (EQUIP) is to improve on the techniques used by Water Survey of Canada technologists to produce winter streamflow estimates. The general approach is to use a combination of conceptual and statistical models to estimate discharge based on available data. Studies of winter streamflow variability are often hampered by a lack of reliable discharge data during periods of ice-cover. However, Department of Indian and Northern Affairs technologists have made frequent winter discharge measurements from 1997 to the present at the Wolf Creek hydrometric station near Whitehorse, Yukon. In this study, these measurements are used to test the application of a conceptual hydrological model for the purpose of estimating winter streamflow. Model performance is also compared against estimates generated by skilled hydrometric technologists using standard Water Survey of Canada techniques. Winter discharge variability was more dynamic than predicted by either the conceptual model or by the technologists. Regression analysis of the model residuals against 5-day antecedent temperature is not significant ($R^2 = 0.02$, $p = 0.275$). Regression analysis of model residuals against 5-day antecedent precipitation shows a weak positive trend ($R^2 = 0.07$, $p = 0.047$). In-stream data (e.g. stage, channel slope or specific conductance data) are likely required to further resolve the variance between model output and observed discharge.

1 Introduction

Discharge computations are typically dependent on the validity of a stable stage-discharge relation to convert observations of stage to discharge. This paradigm is generally acceptable for the production of continuous estimates of discharge during the open water season, but is inadequate for the winter season for two reasons. First, there is no unique and stable stage-discharge relation under the effects of an ice cover. This is due to the frictional effect of the ice cover on the hydraulic conveyance of the stream channel, and to the displacement of water by floating and/or frazil ice in the channel. Secondly, it is difficult to obtain continuous record of stage data in the winter months. Monitoring techniques are best suited for warm weather conditions, when stage data can readily by acquired with the use of stilling wells or with pressure transducers vented to an orifice anchored to the streambed. During the cold season, stilling wells and/or the intake pipes to stilling wells are prone to freezing, anchor ice may form over the pressure transducer's bubbler orifice and either obstruct or displace the orifice, frazil-ice dams can form over the orifice or the ice cover can freeze to bed over the pressure orifice. These problems are particularly acute in northern rivers with a typically shallow, rectangular cross-section profile. In addition, winter weather affects on-shore data logging systems, which are prone to power problems exacerbated by solar panels covered by snow or to problems with the integrity of the plumbing for pressurized systems in extreme cold temperatures.

The Estimation of Discharge Under Ice Project (EQUIP) has the objective of improving the reliability, cost-effectiveness, and timeliness for production of winter streamflow estimates by the Water Survey of Canada. EQUIP is described in more detail in Hamilton et al. (2000). The approach is designed to exploit all of the data that may be relevant to predicting discharge, starting from the case where the only local, in-stream, data are infrequent discharge measurements from a typical monitoring program. In that case, a conceptual hydrological model is used to produce discharge estimates based on temperature and precipitation data from the nearest relevant climate station. Moore et al. (in press) found that storage depletion processes could explain most of the variance in winter hydrographs. A simple hydrological model can determine the storage depletion curve for any winter if initial storage volumes can be specified.

Ouarda et al. (2001) discusses some of the statistical techniques that could be employed if in-stream monitoring data (e.g. stage data) are available. These techniques are not applicable in this case study, because the stilling well at the Wolf Creek gauging station is frozen for the duration of the winter season. Further work is also planned to develop simple hydrodynamic models at the scale of a single channel reach which would use two stage sensors at the upstream and downstream ends of the reach to provide continuous estimates of winter streamflow.

This paper addresses two research questions. First, what is the accuracy and reliability of estimates obtained by application of a conceptual hydrological model as compared to established WSC methodology? Secondly, what can we learn from the deviations from model predictions to improve future generations of the model?

These questions cannot be entirely answered with a single case study. However, opportunities to study winter streamflow are limited to cases where dedicated field campaigns provide high frequency observations of discharge by standard measurement techniques. These campaigns are relatively infrequent (e.g. Chin, 1966, Melcher and Walker, 1992, Hamilton, 1995) and none can be said to be broadly representative. Hamilton et al. (2000) found that a conceptual model provided estimates of winter streamflow for M'Clintock River near Whitehorse that are comparable to the quality of estimates generated by standard WSC techniques and have the advantage of being less reliant on subjective judgement. The Wolf Creek data provided by the Department of Indian and Northern Affairs in Whitehorse, Yukon, provides an opportunity to test the repeatability of those results.

2 Methods

The study area is the Wolf Creek watershed, which has a catchment area of 180 km^2 and is located 15 km south of Whitehorse, Yukon at about 61^o north latitude. Janowicz (1998) provides a more complete description of the geography, climate and research agenda specific to this research basin.

An intensive hydrometric monitoring program including frequent winter streamflow measurements has been in place since 1996 to support research activities related to the Global Water and Energy Cycle Experiment (GEWEX). Two experienced DIAND hydrometric technologists have conducted these measurements, which are made from the ice cover as well as by wading and salt dilution techniques. Measurement error is a distinct possibility (e.g. Pelletier, 1989, Pelletier, 1990), but not addressed in this study.

2.1 Analytical framework

A conceptual hydrological model is used to generate daily discharge estimates. The initial model output is then adjusted to obtain a best fit to the last day of open water and three winter measurements. The calibration measurements are selected as being representative of a ‘typical’ WSC metering program. The model is validated with all remaining measurements for that winter.

Model performance is compared to estimates generated by experienced Water Survey of Canada technologists who use the same calibration data including the antecedent open water hydrograph, temperature and precipitation data, and the same three calibration measurements. The resulting estimates are validated using all remaining measurements for each of the three winters examined.

Model residuals are compared against one, three and five day averages for temperature and precipitation. These averages are calculated for the one, three and five days up to, and including, the date of the measurement.

The following sections provide a more detailed description of the model used and the procedures for applying the model for estimation of winter streamflow.

2.2 Description of model

The model used is a locally developed variant of the HBV model developed by the Swedish Meteorological and Hydrological Institute (Bergstrom 1995; Lindstrom et al. 1997). The version used for EQUIP is described in more detail by Hamilton et al. (2000); however, a simpler reservoir scheme is used for this application. A dual-linear reservoir (e.g. Hamilton and Moore, 1996) provides good results for the purpose of fitting winter hydrographs, and has the advantage of ease of adjustment of storage initial conditions over the non-linear storage model used by Hamilton et al. (2000).

In the absence of inputs of rain and/or snowmelt, and losses by evapotranspiration, discharge (Q) is a function of storage (S):

$$Q = -dS/dt \qquad (1)$$

For a dual-linear reservoir model,

$$S = S_1 + S_2 \qquad (2)$$

and

$$Q = a^{\cdot}S_1 + b^{\cdot}S_2 \qquad (3)$$

where S_1 and S_2 are the amounts of water stored in two reservoirs and a and b are recession coefficients. Solving Equations 1 to 3, subject to the initial condition that $Q_{(t=0)}$ = A+B, where A = $a^{\cdot}S_{1(t=0)}$ and B = $b^{\cdot}S_{2(t=0)}$, yields:

$$Q_t = Ae^{-at} + Be^{-bt} \qquad (4)$$

where Q_t is discharge at time t, and t=0 is the last day of open water conditions (i.e. the start of the time period when rain, snowmelt and evapotranspiration can be considered to be negligible due to sustained sub-freezing temperatures).

This model divides the basin into elevation bands and within each band deals separately with forested, open and lake areas. The model runs on a daily time step using estimates of mean temperature, total rainfall, total snowfall and potential evaporation extrapolated to each elevation zone. Model parameter values and a brief description of parameter function are provided in Table 1.

Table 1 *Model parameter values and brief description*

Parameter	Description	Calibration Value	Units
RFCF	Rainfall correction factor	1.1	
SFCF	Snowfall correction factor	1.3	
PCALTL	Precipitation gradient	0	m^{-1}
TFRAIN	Fraction of rainfall not lost to interception	0.9	
TFSNOW	Fraction of snowfall not lost to interception	0.8	
TLAPSE	Temperature lapse rate	0.007	$^{o}C/m$
TT	Threshold temperature limit for snow/rain	0	^{o}C
TTI	Temperature interval for mixed snow and rain	1	^{o}C
EPGRAD	Fractional rate of decrease of potential evaporation with elevation	0.00011	m^{-1}
ETF	Correction factor for potential evaporation	0.5	$^{o}C^{-1}$
TM	Threshold temperature for snowmelt	1.9	^{o}C
CMIN	Melt factor on winter soltice for open areas	1.9	$mm/^{o}C/d$
ΔC	Increase in melt factor between winter and summer soltices	2	$mm/^{o}C/d$
MRF	Ratio between melt factor in forest to melt factor at open sites	0.5	
CRFR	Threshold temperature for freezing of liquid water in snow	2	^{o}C
WHC	Liquid water holding capacity of the snowpack, as a fraction of snowpack water equivalent	0.05	

Parameter	Description	Calibration Value	Units
LWR	Maximum amount of liquid water that can be retained by snowpack, regardless of snowpack water equivalent	2000	mm
FC	Field capacity of soil	100	mm
LP	Limit for potential evaporation	0.7	
BETA	Exponent in soil drainage function	1.3	
KU	Outflow coefficient (= ‘a’ in Eqs. 3 and 4) of fast reservoir (S_1)	0.26	d^{-1}
Fo	Fraction of catchment contributing to slow runoff	0.57	
KL	Outflow coefficient (= ‘b’ in Eqs. 3 and 4) of slow reservoir (S_2)	0.008	d^{-1}

The model can be run from a ‘cold’ start, requiring only discharge on the first day of the model run, or it can be run from a ‘warm’ start. In a ‘warm’ start, basin water storages are initialized from a file created on the last day of the previous model run. These storages include the ‘upper’ (S_1) and ‘lower’ (S_2) reservoir volumes, as well as snow water equivalent, snow liquid water content, and soil moisture volumes for each land use and elevation band.

2.3 Model calibration

The model was calibrated to data for the period from October 1, 1993 to September 30, 1996. Data for 1997 to 2000 were used to provide an independent test of winter discharge estimates. There were only five winter measurements during the calibration period. A weight factor of 60 was applied to winter measurements and a weight of one was applied to open water data to compensate for under-sampling of winter discharge. The loss function used for calibration is a variant of the Nash-Sutcliffe Model Efficiency (NSME) calculated as:

$$\mathrm{NSME} = 1 - \left[\sum_{i=1}^{n} \mathrm{w_i} (\mathrm{Q_{p(i)}} - \mathrm{Q_{o(i)}})^2 \Big/ \sum_{i=1}^{n} \Big(w_i Q_{o(i)} - \overline{Q_p})^2 \Big)^2 \right] \qquad (5)$$

where $Q_{p(i)}$ is predicted discharge at time i, $Q_{o(i)}$ is observed discharge at time i, w_i is the weight factor applied to an observation of discharge at time i and

$$\overline{\mathrm{Q}}_\mathrm{p} = \sum_{i=1}^{n} \mathrm{w_i Q_{p(i)}} \Big/ \sum_{i=1}^{n} \mathrm{w_i} \qquad (6)$$

2.4 Procedure for updating model output

The model was run twice for each simulation. The first run was made for the whole year to get a first guess of the storage volumes at the end of the open water period. This run is referred to as “uncorrected” in the next section. A second model run starts from the last day of open water, and is initialized with storage volumes calibrated to the last day of open water and to three winter measurements. This model run is referred to as ‘adjusted’ in the next section. The procedure for updating initial storage estimates is explained below.

The model is initialized on June 1st with storages from the previous year for a 'warm' start, and run through to May 31st of the following year to obtain a first estimate of the storage volumes (S_1 and S_2) valid for the last day of open water conditions. Equations 1 to 3 are used to adjust these estimates of storage volume, minimizing the sum of squared fractional errors (SSFE):

$$\mathrm{SSFE} = \sum_{i=1}^{n} \left[\left(\mathrm{Q}_{\mathrm{o(i)}} - \mathrm{Q}_{\mathrm{p(i)}} \right) / \mathrm{Qo(i)} \right]^2 \qquad (7)$$

for the last day of open water and three winter measurements. The three winter measurements are pre-selected as being representative of the timing of a 'typical' WSC monitoring program.

2.5 Procedure for subjective interpolation by climatic comparison

In the absence of valid stage data, WSC technologists typically prepare estimates of daily winter discharge for publication by hydrograph interpolation. These estimates are distinguished in WSC publications with a flag of 'B' for backwater conditions. Other methods may be used, if stage data are available and only the stage-discharge relation is invalid. These techniques are discussed by other authors (e.g. Rosenberg and Pentland, 1983, Walker, 1991, Melcher and Walker, 1992) but are not considered here because of a lack of stage data for Wolf Creek.

To prepare estimates of winter streamflow by the interpolation method, a hydrograph is prepared with open water discharge data for the fall and spring, spanning the winter for which estimates are required. Winter measurements are plotted on the hydrograph, and the technologist interpolates between the plotted points on the hydrograph using temperature and precipitation data for guidance. In general, the technologist will try to fit a smooth recession curve through the points, and then modify the curve according to personal judgement about how sensitive the stream is to temperature or precipitation effects. Four Water Survey of Canada technologists were asked to estimate discharge for three winters for Wolf Creek based on three winter measurements representing a typical monitoring program. All remaining measurements are used for verification. The performance statistic chosen for verification of estimates is the mean absolute fractional error (MAFE):

$$\mathrm{MAFE} = \frac{\sum_{i=1}^{n} \left| \left(\mathrm{Q}_{\mathrm{o(i)}} - \mathrm{Q}_{\mathrm{p(i)}} \right) / \mathrm{Q}_{\mathrm{o(i)}} \right|}{\mathrm{n}} \qquad (8)$$

This statistic is unbiased by discharge magnitude, and is not unduly influenced by outliers, as would a statistic based on squared error.

3 Results

Examination of the hydrographs generated both by the model and by the four technologists (Figure 1) shows that neither the model nor the technologists have consistent skill for predicting winter streamflow for Wolf Creek. For example, there are three measurements in the fall of 1997, three measurements in the fall of 1998 and one measurement in the fall of 1999 that are distinct outliers. There are also two clusters of outliers in the winter of 1998/99 with respect to the modeled recession trend. The first cluster of measurements, from October to the end of January, plot well above the recession and a second cluster, in February and March, plot well below the recession trend.

The MAFE statistics (Table 2), range from 23.7% (97/98) to 96.4% (98/99) for the model, and from 23.2% (97/98) to 111.2% (98/99) for the technologists. Overall, the model does marginally better than the technologists with a mean statistic for all three years of 56.1% compared to 64.0%.

The statistics for the mean and the median for each of the winters (Table 2) show that the technologists generally out-perform the model on a seasonal basis. For example, during the winter of 1989/99 the average of the technologists estimates for the seasonal mean and median at 0.170 and 0.195 m^3/s were much closer to the observed values of 0.171 and 0.l55 m^3/s than the model estimates, which were 0.05 and 0.024 m^3/s, respectively.

The annual minimum discharge often occurs during the winter months in northern streams. An accurate estimate of this statistic is required for many engineering and fisheries related activities. Estimates of the minima by the model and all four technologists (Table 2) are fairly close to the observed minima for 1997/98 and 1999/00. However, the observed minimum for 1998/99 was over-predicted by the model and by all four technologists.

Estimates of discharge for any given day can vary widely. For example on January 12, 1999, a discharge of 0.265 m^3/s was measured. The modeled discharge for that date was 0.01 m^3/s, and the technologists estimated 0.125, 0.005, 0.061, and 0.006 m^3/s respectively. On November 3, 1999, a discharge of 0.092 m^3/s was measured. The modeled discharge for that date was 0.28 m^3/s and the technologists estimated 0.41, 0.37, 0.55 and 0.36 m^3/s, respectively, showing that singular estimates of discharge can be in error by over 500% in extreme instances.

Table 2 *Descriptive and performance statistics for winter streamflow predictions. Statistics are provided for 49 verification measurements over 3 winters for: observed discharge, the uncorrected model, the model adjusted to 3 calibration measurements, and for each of 4 technologists, shown here as A, B, C, and D.*

	Observed	Uncorrected	Adjusted	A	B	C	D	All tech's
All Years								
MAFE		107.6%	56.1%	68.1%	73.1%	55.4%	59.2%	64.0%
Mean (m^3/s)	0.212	0.164	0.181	0.224	0.206	0.252	0.258	0.235
Median (m^3/s)	0.226	0.149	0.164	0.208	0.210	0.268	0.280	0.242
Standard Deviation	0.124	0.084	0.150	0.151	0.169	0.159	0.159	0.160
Minimum (m^3/s)	0.002	0.039	0.010	0.011	0.004	0.007	0.006	0.004
Maximum (m^3/s)	0.437	0.380	0.587	0.620	0.775	0.562	0.640	0.775
Count	49	49	49	49	49	49	49	49
97/98								
MAFE		28.1%	23.7%	28.4%	37.0%	23.2%	27.3%	29.0%
Mean (m^3/s)	0.284	0.217	0.332	0.294	0.302	0.330	0.340	0.316
Median (m^3/s)	0.254	0.208	0.302	0.220	0.230	0.304	0.300	0.264

	Observed	Uncorrected	Adjusted	A	B	C	D	All tech's
Standard Deviation	0.081	0.082	0.127	0.149	0.194	0.116	0.145	0.151
Minimum (m^3/s)	0.164	0.106	0.164	0.188	0.127	0.169	0.150	0.127
Maximum (m^3/s)	0.437	0.380	0.587	0.620	0.775	0.562	0.640	0.775
Count	17	17	17	17	17	17	17	17
98/99								
MAFE		249.9%	96.4%	111.2%	113.8%	62.1%	60.7%	87.0%
Mean (m^3/s)	0.171	0.109	0.050	0.178	0.146	0.175	0.181	0.170
Median (m^3/s)	0.155	0.097	0.024	0.170	0.190	0.210	0.210	0.195
Standard Deviation	0.140	0.067	0.061	0.137	0.130	0.149	0.154	0.142
Minimum (m^3/s)	0.002	0.039	0.010	0.011	0.004	0.007	0.006	0.004
Maximum (m^3/s)	0.425	0.266	0.231	0.400	0.310	0.380	0.370	0.400
Count	19	19	19	19	19	19	19	19
99/00								
MAFE		45.0%	48.3%	64.8%	68.4%	81.0%	89.8%	76.0%
Mean (m^3/s)	0.176	0.174	0.173	0.202	0.170	0.261	0.263	0.224
Median (m^3/s)	0.116	0.155	0.154	0.095	0.075	0.183	0.240	0.148
Standard Deviation	0.109	0.060	0.060	0.151	0.135	0.180	0.135	0.150
Minimum (m^3/s)	0.090	0.100	0.099	0.075	0.050	0.080	0.075	0.050
Maximum (m^3/s)	0.394	0.287	0.287	0.420	0.370	0.553	0.460	0.553
Count	13	13	13	13	13	13	13	13

The adjustment of the model to the three winter calibration measurements contributes substantial skill to model performance, reducing the MAFE statistic from over 100% to slightly over 50% average error.

Plots of predicted against observed discharge for both the model and the technologists are shown in Figure 2. A 1:1 line is shown for reference. Perfect predictions would plot on the line. Both plots show a similar pattern and range of error, but differ slightly in bias.

3.1 Analysis of model residuals

Model errors are not correlated to temperature as can be seen in the scatter graphs in Figure 3. This visual evidence is supported by the regression statistics in Table 3. A positive correlation between model error and 5-day antecedent precipitation is statistically significant, although one and three-day precipitation accumulations are not significant.

Table 3 Regression statistics for scatter plots shown in Figure 3

	R^2	p statistic
One-day temperature (T1)	0.01	0.463
Three-day temperature (T3)	0.02	0.342
Five-day temperature (T5)	0.02	0.275
One-day Precipitation (P1)	0.01	0.374
Three-day precipitation (P3)	0.05	0.102
Five-day precipitation (P5)	0.07	0.047

4 Discussion

In a previous study, Hamilton et al., (2000) found errors for both subjective and model predictions to be in the range of 10 to 15% for the M'Clintock River near Whitehorse. The relatively large errors found for Wolf Creek in this study (~50 to 70%) may indicate that the use of conceptual modeling for winter streamflow estimation is limited by basin scale. The M'Clintock River is larger than Wolf Creek by almost an order of magnitude (1700 km^2 compared to 180 km^2). This apparent difference in performance may be a result of poorly understood or unknown hydrological or hydraulic processes that introduce variability at the scale of a small basin but which are relatively insignificant at the scale of a large catchment, leaving storage depletion processes as the dominant signal for large basins.

The model did a poor job of predicting the mean discharge during the winter of 1998/99. The model assumption of a smoothly varying storage depletion process cannot be supported by observations showing step-function storage depletion. With the exception of a few anomalies, the fall recession was very flat until late January 1999. A rapid drop in discharge occurred in late January resulting in late winter discharge values as low as 0.002 m^3/s on March 23rd, 1999.

Low late-winter discharge in the spring of 1999 may be caused, at least in part, by containment of Coal Lake discharge by a lake-outlet ice dam. Jasek and Ford (1998) describe an episode of containment of water in Coal Lake, with a subsequent outburst flood when an ice dam at the lake outlet released in the spring of 1996. Coal Lake is a 1-km^2 lake located on the upper reaches of the main stem of Wolf Creek. Temperatures during the winter of 1998/99 were cool during the period in question, and relatively dry antecedent conditions may have pre-disposed the lake outlet to freeze to bed.

It is unlikely that ice-effects at the outlet of Coal Lake can entirely explain the apparent step-function hydrograph of 1998/99. Hamilton et al. (1996) proposed that there might be a systematic sample bias with some early-winter discharge measurements. This sample bias arises as a result of channel storage processes that are active on a diurnal time scale, while most measurements of winter discharge are made during mid-day. A complete ice cover typically does not form on Wolf creek until mid-winter due to relatively warm groundwater inputs. Open reaches of the stream are prone to anchor-ice production, which tends to form during clear, cold nights. Daytime warming causes a release of this anchor ice resulting in a subsequent release of channel storage. Hence daytime measurements of discharge may not be representative of 24-hour average discharge. If true, this may explain the apparent lack of recession during the early-winter season in 1998/99 and 1999/00.

The measurements that plot as outliers in the fall of all three winters may be due to discharge depression events. Hamilton and Moore (1996) documented evidence of this process in two near-by groundwater dominated streams and Moore et al. (in press) found that 50% of Yukon hydrometric stations exhibited evidence of a discharge depression for years when a measurement was obtained within 10 days of freeze-up. Stream-aquifer interactions as proposed by Hamilton (1995) may also contribute to the anomalous discharge patterns evident in the early winter for all three years.

The poor correlations of both temperature and precipitation with model residuals indicate that the simple snow routines in the model are adequate for capturing gross climatic effects on winter discharge variability. The trend in the pattern of residuals against five-day precipitation accumulations is likely too weak to lead to improved techniques for estimating winter discharge. There are three points on the plot with high leverage contributing to the apparent trend. These points are all from the 1998/99 year, for which the model assumptions are apparently not valid. However, if this slight tendency of the model to under-predict discharge for high five-day precipitation accumulations is not a statistical artefact, it may be due to processes not represented in the model. For example, Kuusisto (1984) found that increased hydrostatic pressure caused by snow accumulation on Finnish lakes resulted in discharge increases at the lake outlets. Further investigation would be required to verify whether the same phenomenon is responsible for the trend observed in this study.

The four WSC technologists did a good job of characterizing the winter hydrographs, given the limited information that they had to work with. They were all able to accurately estimate mean and minimum discharge on a seasonal scale. However, inconsistencies in daily estimates of discharge indicate that interpolation with climatic comparison is an inappropriate technique for estimating daily discharge at Wolf Creek. This finding could be generalized by saying that hydrograph interpolation techniques should be limited to streams for which the hydrological and hydraulic processes contributing to streamflow variability are well understood. This result reinforces the conclusion of Rosenberg and Pentland (1983) that the three methods examined in that study (including the hydrograph interpolation method, as well as two methods based on the use of stage data) are inadequate for small streams. Daily discharge estimates for small basins will improve with in-stream monitoring (e.g., index velocity, channel slope, or specific conductance) and frequent actual discharge measurements.

One of the technologists returned a hydrograph with a hand written comment “something wrong with this discharge – check note” about the calibration measurement on April 6, 1998 (0.162 m^3/s), illustrating a common problem with winter discharge computations. It is usually months after the fact that a technologist may question a winter measurement while trying to make sense of the few data points at his/her disposal for making winter estimates. By this time, it is too late to address the problem, real or perceived. One outcome of the EQUIP project is that technologists may be able to use model-simulated streamflow to determine whether a given measurement is ‘in the ballpark’ while still in the field, and thus able to conduct a verification measurement.

5 Conclusions

Two research questions were addressed in this study. The first question was: what is the accuracy and reliability of estimates obtained by application of a conceptual hydrological model as compared to established WSC methodology? The answer to this question is that for the Wolf Creek hydrometric station the accuracy of the conceptual hydrological model is similar to the accuracy of established WSC methodology. However, the model does a poor job if the basic model assumptions are not valid for the hydrograph being simulated (e.g. 1998/99). A wide range in individual technologist estimates of daily discharge indicates that the model technique may generally be more reliable because it is reproducible. The second question was: what can we learn from the deviations from model predictions to improve future generations of the model?

Analysis of the model residuals indicates that there is little additional information that can be extracted from temperature and precipitation data as predictive variables. However, the magnitude of the residuals indicates that there are sources of discharge variability that the model cannot explain. Unfortunately, established WSC methodology is also inadequate to represent discharge variability at this scale, which effectively precludes the use of published hydrometric data to further investigate these processes. Dedicated field campaigns will likely be required to fully understand the relevant processes of winter hydrology.

Present trends in monitoring technology are unlikely to advance sufficiently in the next few years to provide continuous discharge monitoring capacity for remote northern streams. Estimation techniques will have to continue to evolve to meet the ongoing need for discharge data. Further testing to refine the limitations of the hydrological modeling approach will proceed, in parallel with testing and evaluation of advanced statistical and hydrodynamic techniques that can be used to estimate discharge for gauging stations where continuous monitoring is achievable.

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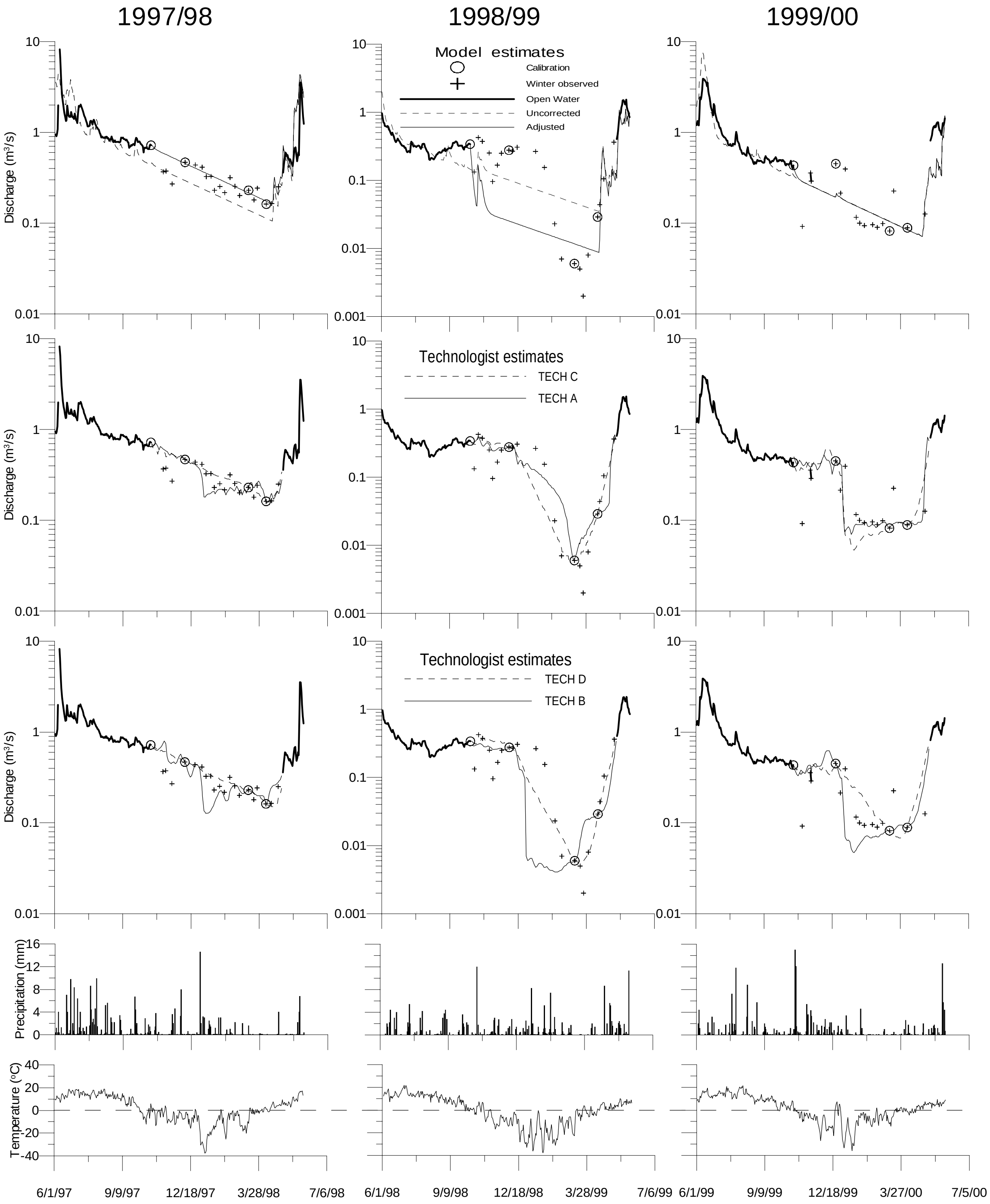

Figure 1 Hydrographs for the three winters studied, showing estimates generated by the model and by four technologists (A,B,C, & D). Please note that the ordinate scale originates at 0.01 for 1997/98 and 1999/00, but originates at 0.001 for 1998/99.

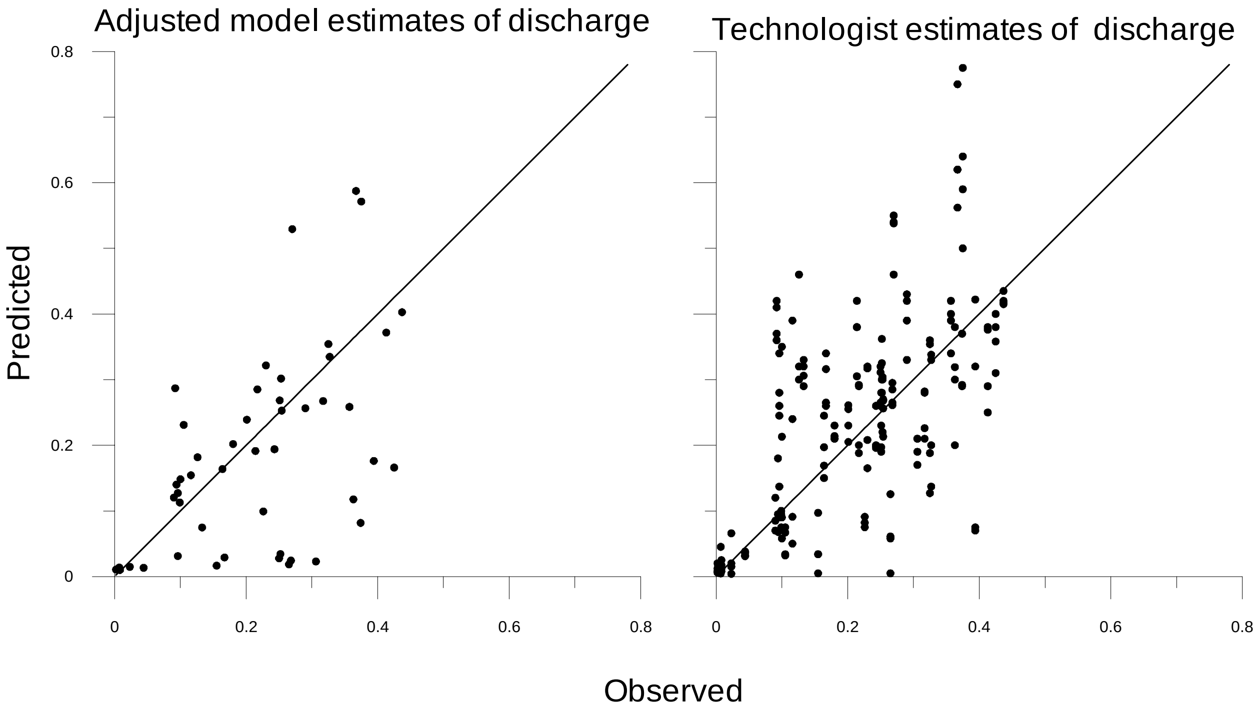

Figure 2 Scatter plots of predicted against observed discharge (m^3/s), n= 49 for model estimates, n= 196 for technologist estimates

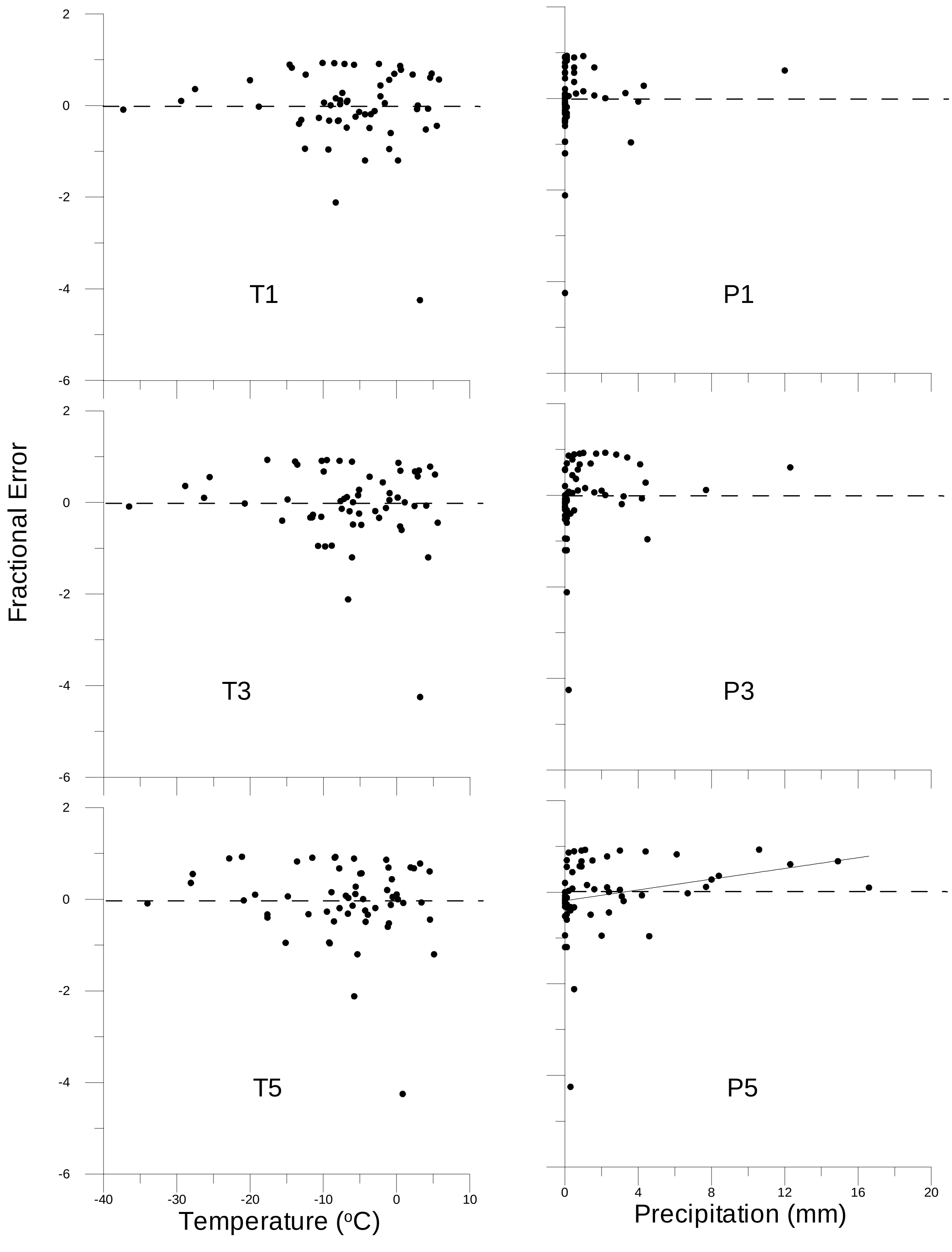

Figure 3 Plots of model residuals against temperature and precipitation averaged over 1,3 and 5 days antecedant to, and including, day of measurement. Refer to Table 3 for regression statistics. A regression line is shown for the only statistically significant regression (P5).