Using Oxygen Isotope Tracers to Evaluate & Optimise Flow Components Generated by the UBC Watershed Model in a Mountainous Basin

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ABSTRACT

Two separate run sequences of the UBC watershed model (UBCWM) were performed for the Bow River at Banff during hydrological years 1996 – 99. Firstly, 1996 and 1997 were calibrated independently to maximise the chance of good calibration results to facilitate a test of isotopic model evaluation. A second continuous model run was performed from 1996 - 99 to test the use of stable oxygen isotopes to assist model optimisation. UBC modelled hydrological end-member proportions were aggregated to a monthly time step and multiplied by their respective $\delta^{18}O$ signatures (from Hopkinson and English, this issue) and summed to provide an overall modelled river $\delta^{18}O$ signature.

After comparing modelled and observed river isotope chemographs for 1996 and 1997, it was found that better results were obtained if the temporal variation in end-member $\delta^{18}O$ signatures was accounted for in chemograph generation. For the statistically optimised 1996 - 99 model run, the observed and modelled chemographs did not compare well. However, there was some improvement following a recalibration after the modelled chemograph indicated that the hydrograph was too responsive and dominated by rainfall. Despite reasonable calibrations (r^2 from 0.83 to 0.93) the model runs always predicted heavier and more variable isotope signatures than observed. Problems with flow routing, orographic enhancement, snowpack accumulation and glacial melt parameters and algorithms were thought to lead to a systematic over-estimation of modelled rainfall which was compensated by an under-estimation of modelled snow and ice. The use of isotopic tracers for hydrological model evaluation and optimisation has been demonstrated.

INTRODUCTION

This paper investigates the use of conservative stable oxygen isotope tracers to assess the accuracy of water balance predictions within a hydrological model used in mountainous basins.

Hydrological models can be calibrated to recreate past hydrographs with high statistical efficiency. Even in large hydrometeorologically complex mountainous basins, Nash-Sutcliffe efficiencies (indicating volumetric and temporal model hydrograph accuracy) greater than 90% can be obtained over inter-annual periods (e.g. Kite and Kouwen, 1992). These relatively high efficiencies tend to imply that the hydrological balance predicted by such model calibrations is accurate. Even if a low efficiency is obtained with the available input data, it may be very difficult to decide which hydrological balance components have been over- or under-estimated. This is an important consideration if the model is used for predictions of future water yields, particularly in

environments where the hydrological breakdown of components is not well understood. For example, Zawadzki (1997) used the UBC Watershed Model (UBCWM) to assess changes to the future river flow regime in the Canadian Rockies given a 2 x CO_2 scenario and reduced glacial extents. Despite reasonable model calibrations, the results raised a question as to the accuracy of the modelled glacial melt contribution, a key component of the study. For large increases in temperature, the commensurate increases in glacial ice melt were relatively low (Zawadzki, 1997). Therefore, regardless of the overall efficiency of any model calibration, the temporal and volumetric accuracy of the hydrological balance prediction remains questionable.

In this paper, monthly balances for hydrological years 1996 to 1997 and 1996 to 1999 have been generated from two separate runs of the UBCWM for the Bow River at Banff (2230 km^2) in the Canadian Rockies. The first run was performed to test the utility of using stable isotope tracers for model evaluation on two independently calibrated years of high efficiency. In the second model run a typical inter-annual time series of diverse hydrological years was statistically optimised. Measured $\delta^{18}O$ signatures for each of the hydrological balance components have been *plugged* into the model to generate a $\delta^{18}O$ chemograph. The validity of the UBCWM predicted hydrological balances is investigated and improvements to the optimised parameter sets are explored by comparing the modelled and observed isotope chemographs.

STUDY AREA

The Bow Valley above Banff (Figure 1) was chosen for this study as it is largely undeveloped and is relatively rich in hydrometeorological data. The basin ranges in elevation from 1350–3500 m.a.s.l and drains the eastern side of the Canadian Rocky Mountains between latitudes 51 and 52° (N). It is largely underlain by carbonate rocks and deep valley tills, has about 50% natural forest coverage, is 3% glacierised and has a dendritic river network containing many small lakes. The average annual temperature at Banff is approximately +3°C but temperatures in this region can dip down to as low as -35°C in winter and rise up to +35°C in summer (Gadd, 1995). Precipitation yields can be over 500 mm higher in the mountainous headwaters than in the agricultural prairie lands downstream. The hydrological regime in the basin has been investigated in recent studies: Hopkinson & Young (1998) discerned the proportional contributions of inter-annual glacier wastage to river flow, while Zawadzki (1997) used the UBCWM to forecast changes to the river's flow regime in a situation of potential future climatic change. A further study, carried out by Grasby (1997), investigated controls on the hydrogeochemistry of the Bow River.
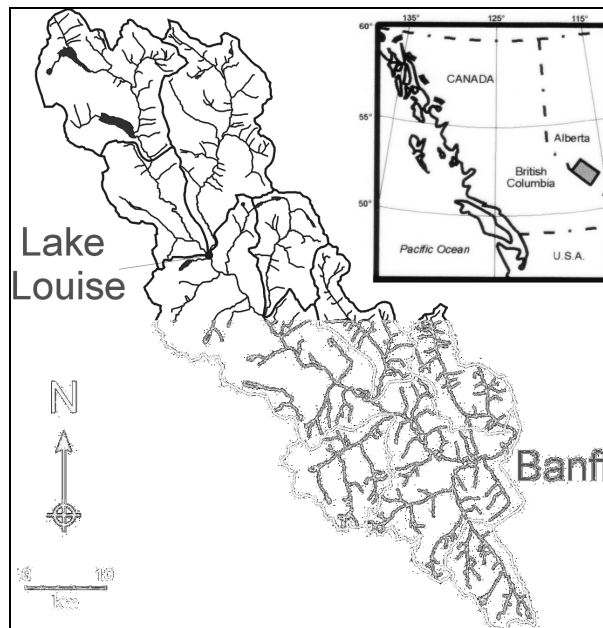
Figure 1. The Bow Valley above Banff showing river network.

MODELLING RIVER DISCHARGE

The UBC Watershed Model

The UBC Watershed Model was designed to provide an overview of watershed behaviour in mountainous areas (see Figure 2 for a schematic overview). A hydrograph is constructed from snowmelt, rainfall and glacier runoff. The model considers snowpack accumulation and ablation, glacier melt, soil moisture, evapotranspiration, groundwater storage, surface and subsurface runoff. Unlike other spatially distributed models, the UBCWM divides the basin being modelled into elevation bands to account for the elevational dependence of key input data and transfer parameters/algorithms. Landcover distribution is facilitated by specifying elevation band proportions of forest, glacier, bare ground and lake coverages. Orientation of forest and glacier cover proportions can also be factored into the model routine to partially account for slope aspect and shading. Model parameter values for balance, storage and routing algorithms can be user specified or calculated by the model using a statistical optimisation routine to give the best overall model performance. (See Quick & Pipes (1977 and 1996) for further details.) To accommodate the general scarcity of meteorological data in remote mountain areas, the model requires only maximum and minimum temperature and daily precipitation. From these input data, the model delivers daily outputs of the following:

- total flow at the basin endpoint;
- snowpack growth or depletion per elevation band;
- soil moisture budget;
- a breakdown of surface runoff, interflow, upper and lower groundwater routing pathways;
- a hydrological balance of snow, ice and rainfall for the three upper (quicker) flow paths.
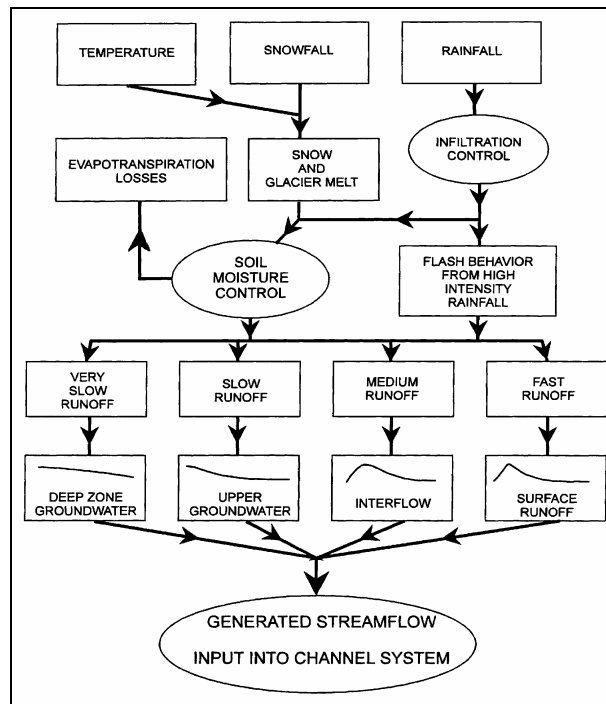
Figure 2. Schematic diagram of the UBC Watershed Model structure (Quick & Pipes, 1996)

The algorithm for glacial melt input (important in climate and landcover change studies) assumes that glacierised areas are simply infinitely deep snowpacks with a low albedo. The lack of a glacial storage algorithm (such as suggested by Moore, 1993), however, was earlier thought to lead to a mis-representation of flow peaks in the hydrograph, particularly later in the melt season when flow through glaciers is most prone to storage lags (Fountain & Tangborn, 1985).

The UBCWM has been used in an attempt to predict future flow regimes in the Bow Valley, Alberta resulting from possible CO_2 induced climatic change (Zawadzki, 1997). However, uncertainty surrounding the validity of hydrological balance predictions during model calibration (Zawadzki, 1997) naturally leads to reduced confidence in future flow predictions. A further utility of the UBCWM was as a flow component based chemistry simulator (Hudson & Quick, 1997). By assigning chemical signatures to each of the flow path zones (surface, interflow, upper and lower groundwater) within the model, Hudson & Quick (1997) were able to simulate stream water chemistry. Their results compared favourably with observations.

The UBCWM was chosen for this study as it was designed for and is operationally used in basins similar in climatic regime, size, relief and ground cover to the Bow Valley and can handle the limited data available in this study area. It is important to note that the aim here is not to draw conclusions about the UBCWM but rather investigate areas in which the calibrations of the model may be in error, despite obtaining reasonable statistical efficiencies.

Model Runs

A watershed calibration description file was generated containing landcover and user specified parametric data. Discharge data for the Bow River at Banff, precipitation and temperature data from Castle Mountain, approximately in the centre of the basin at an altitude of 1500 m.a.s.l., were then formatted for use within the model. Further temperature data from Banff, 1300 m.a.s.l., and Lake Louise, 1650 m.a.s.l., were also used in model runs. Basin-wide precipitation was extrapolated from Castle Mountain Village. An orographic enhancement factor of 3% per 100 m was used to calculate precipitation for elevations up to 2200 m.a.s.l. and 6% per 100 m above 2200 m.a.s.l. These values were based on observations of local snow course data and

a sensitivity analysis of the parameter values (Zawadzki, 1997). The model divides precipitation into snow or rain for each elevation band. When the mean daily temperature in a given elevation band is over 2°C, all precipitation is liquid. Precipitation falling at temperatures below 0°C is considered snow. If the daily temperature is between these values, the precipitation is specified as mixed rain and snow. Temperature lapse rates, snow and ice melt, evapotranspiration, wind and cloud cover were modelled using default parameters.

Groundwater percolation rates and residence time data were not available so flow routing parameters were optimised within the model. Groundwater percolation was thus assigned a maximum value of 5 mm per day. Any hydrological input exceeding this was shifted to interflow. Of this excess, 55% was arbitrarily sent to the deep zone share and 45% to the upper zone. A discharge constant of 80 days was computed for the upper zone and the deep zone was assigned a 130-day discharge constant. The efficiency of the calibration was reasonable for 1996 with an overall efficiency of 93%. When this calibration was applied to 1997 data, efficiency dropped considerably due to winter precipitation being overestimated. Model output improved if snowfall was reduced in all elevation bands by 8% in the precipitation modelling routine. This increased the efficiency to 90% for the entire year. Using two different calibrations to account for the slight differences in hydrological character for each year was thought to give the model the "best chance" of generating accurate predictions of the hydrological balance. The output of the UBCWM was broken down into three "fast" runoff and/or "interflow" components: snowmelt, glacial icemelt, rainfall and a fourth component of groundwater baseflow. The observed and modelled hydrograph at Banff, along with these four flow components, are illustrated in Figure 3.

A completely optimised run of the model was performed from 1996 to 1999 as one continuous time series. This time series is of significant interest because it spans years of diverse hydrological characteristics. 1996, 97 and 99 were all deep snowpack years. However, 1998 was an *El Niño* year and as such was one of the driest years on record in this region. Calibrating a model over such a range of hydrological conditions is a challenge but these are the conditions a model has to deal with if it is to be used in long term studies to assess climate and landcover changes. This model run provided an interesting test of the isotopic model evaluation process.

Two meteorological weather stations had data available from 1996 to 1999 (Castle Mountain Village, 1500 m.a.s.l. and Bow Summit, 2100 m.a.s.l.). There were some gaps in the records and these were filled by regressing parts of the time series with other nearby stations. The basin-wide orographic enhancement parameter was set by extrapolating from the records of these two stations. Unlike the prior run, parameter values for the entire time series were set using standard statistical optimisation procedures within the UBCWM (Quick and Pipes, 1996). A coefficient of determination of 83% was obtained and the modelled hydrograph is illustrated in Figure 4. This model calibration was thought to be more typical of what might occur during operational model runs for forecasting purposes or during climatic change impact studies.
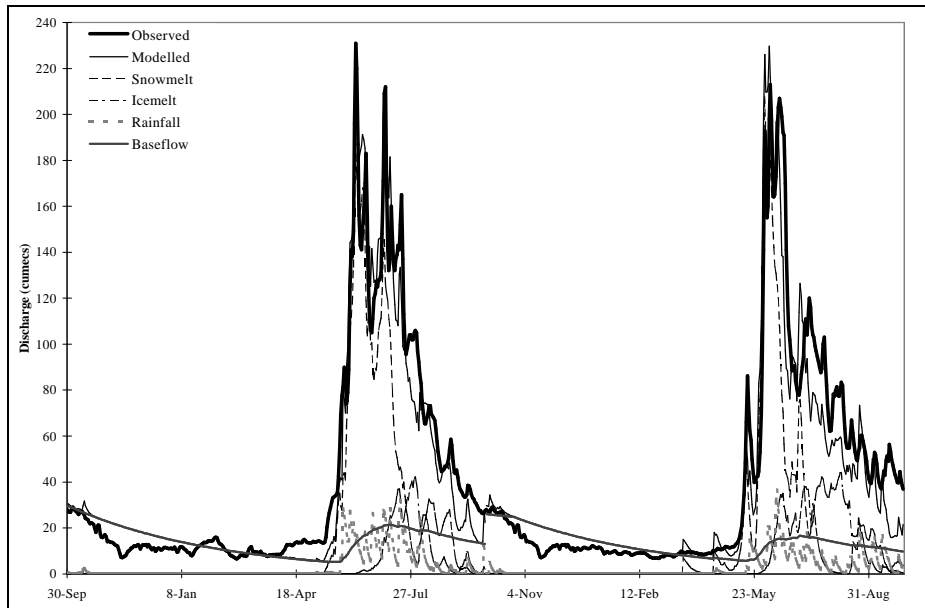
Figure 3. Observed and modelled river flow and end-member components at Banff, 1996-97 hydrological years (years calibrated individually, 1996 $r^2 = 0.93$, 1997 $r^2 = 0.90$).
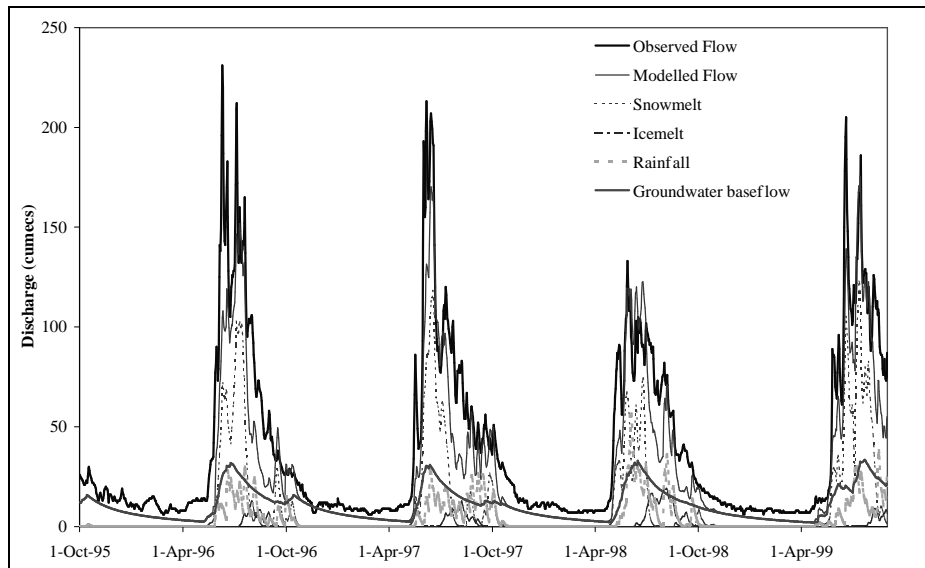

Figure 4. Observed and modelled river flow (second run) and components at Banff, 1996-1999 hydrological years. First run $r^2 = 0.83$, second run $r^2 = 0.88$

MODELLING THE RIVER δ^{18}O CHEMOGRAPH

The sampling methodology and end-member δ^{18}O characteristics of hydrological flow components within the Bow Valley above Banff were summarised in an accompanying paper (Hopkinson and English, this issue). Two approaches have been used to assign appropriate isotope signatures to each flow component of the UBCWM simulated hydrological balance. The first was to assume average or "static" δ^{18}O values from the sample data (Table 1) for each of the four end-members. This provided a simple first round model to assess whether or not this technique had potential and also provided a reference for subsequent improvements. The second approach incorporated the temporally changing or "dynamic" hydrological balance signatures (Table 1) over

the course of each melt season. These two signature sets were first applied to the two independently modelled years, 1996 and 1997. Then the dynamic end-member signatures were applied to the continuously modelled time series from 1996 to 1999. Finally, the dynamic isotope signatures were applied to the four-year time series a second time following the interpretation of potential errors in the UBCWM calculated balance from the previous model run.

Table 1. Static and temporal generalisations of hydrological end-member $\delta^{18}O$ signatures within the Bow Valley above Banff from observations by Hopkinson and English (this issue).

Static isotope signatures ($^{o}/_{oo}$)		Dynamic isotope signatures ($^{o}/_{oo}$)	
Snow	Avg = -22.2 s = 1.4 n = 20	Hydrological years: 1996 = 1997 = 1998 = 1999 =	-22.3 (s = 1.5, n = 6) -22.3 (estimated from 1996) -21.6 (s = 1.6, n = 7) -22.6 (s = 1.0, n = 6)
Ice	Avg = -20.9 s = 0.7 n = 23	All years: May = June = July = August = September =	-21.5 -21.3 -21.0 -20.8 -20.5
Rain	Avg = -12.6 s = 2.2 n = 16	Constant signature:	-13
Baseflow	Avg = -20.5 s = 0.05 n = 9 (winter samples only)	December to April of each year = -20.5 Baseflow depletes to a minimum during August each year: 1996 = 1997 = 1998 = 1999 =	 -21.0 -21.0 -20.6 -21.4

River samples were collected every week during the summers of 1996 and 1997 and approximately every other week during 1998 and 1999. The samples were analysed for $\delta^{18}O$ (as described in Hopkinson and English, this issue) and then volume weighted according to river flow at Banff and aggregated to a monthly time step. Each of the modelled flow components was also aggregated to the same time step and its proportion of the hydrograph multiplied by its respective $\delta^{18}O$ signature. These values were then summed and a modelled chemograph estimated. In Figure 5, the observed isotope chemograph is plotted (both raw data and volume weighted) along with the first modelled chemograph using static isotope signatures. The sensitivity of the modelled chemographs to changing end-member $\delta^{18}O$ signatures was investigated by generating the chemographs two more times using the standard deviation of error either way in the end-member signatures. In the case of baseflow, a summertime standard deviation was not available so a value of $^{+}/_{-}$ 0.5 $^{o}/_{oo}$ was used, despite the small change observed during winter months, to account for unknown changes during the summer.

ISOTOPIC MODEL EVALUATION AND OPTIMISATION

Static Isotope Signatures for UBC Model Run 1

For the chemograph modelled with static $\delta^{18}O$ signatures (Figure 5), the modelled isotope chemograph was never lighter than observed in the river. The volume weighted average isotope signatures for the entire study period differ by over 0.3 $^{o}/_{oo}$ and, during September 1997, the observed chemograph was lighter than predicted by the model even when each of the components was lightened (depleted) by 1 standard deviation. However, the overall shape of the chemograph was at least approximately correct and, for the most part, did lie within the standard deviation range. It was simply exaggerated in one direction, i.e. it was generally too heavy or isotopically enriched. There are several reasons why this may have occurred but before discussing these reasons, observations of the dynamic chemograph model for the same time period will be outlined.
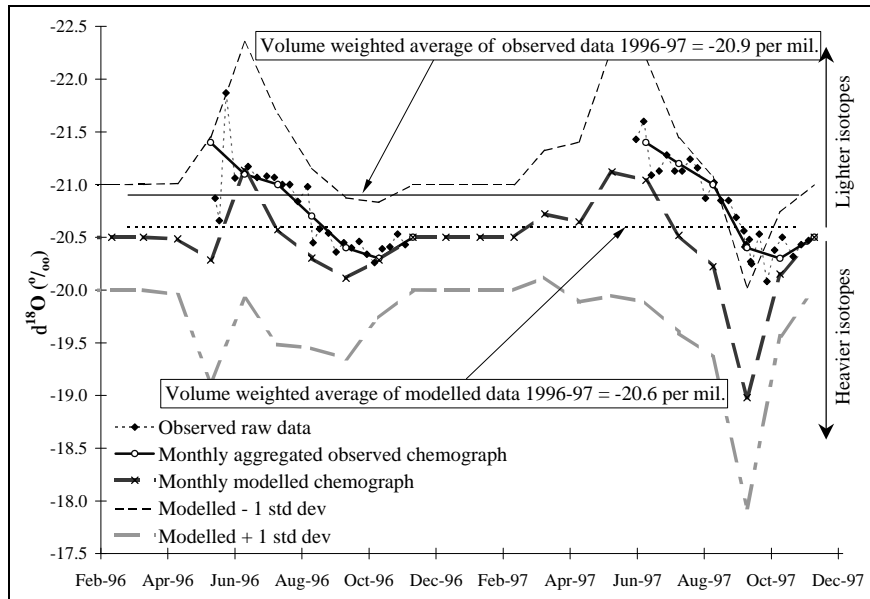
Figure 5. Observed, aggregated and modelled $\delta^{18}O$ river signatures for the Bow at Banff, 1996 – 1997 (static flow component signatures).

Dynamic Isotope Signatures for UBC Model Run 1

As with the first chemograph using static isotope signatures, the modelled values using dynamic signatures were generally too heavy (Figure 6). The difference between observed and modelled river isotope signatures for the study period was reduced, however, to 0.2 $^{o}/_{oo}$ (almost within the range of analytical error). This is a visible improvement but the fact that it is only slightly better than the static signature graph suggests that the effort taken to characterise inter-annual and seasonal variations in isotope signatures may only provide minimal returns. This, in turn, suggests that if this technique of isotopic model evaluation is found to be useful, then the static signature method could be a robust first round approach.
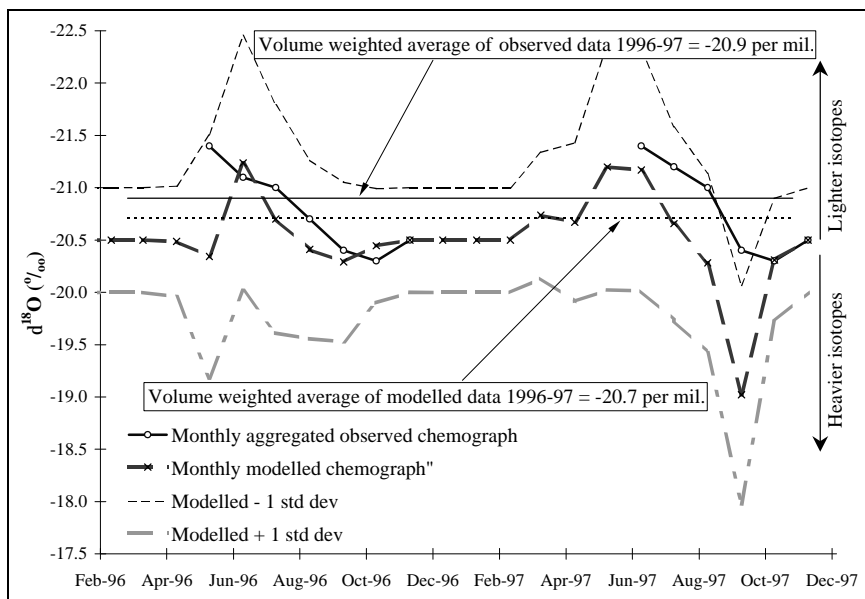

Figure 6. Aggregated observed and modelled monthly $\delta^{18}O$ river signatures for the Bow at Banff, 1996 – 1997 (dynamic flow component signatures).

Three potential reasons for the difference between the modelled and observed chemographs have been considered:

1. the $\delta^{18}O$ values attributed to the four modelled flow components are in error;
2. the $\delta^{18}O$ signature changes during transit along the course of the river;
3. the predicted balance is in error.

In the case of snow, the signature may change due to preferential initial melting of lighter isotopes early on (Maul & Stein, 1990) and this could cause the large difference between observed and modelled chemographs in spring of both years but over the year the bulk snowpack signature should even out. The static signature applied to ice in this area is corroborated in unpublished data by West (1972) and it should be noted that late summer runoff in the glacierised headwaters is found to have a similar signature. The majority of rain samples were taken from valley locations, which could potentially bias rain with a heavy signature. However, those rainfall samples taken from high elevations did not indicate isotopic depletion with elevation (Hopkinson and English, this issue). It is possible that the sampling strategies were inadequate to characterise the components but considering the relatively low standard deviations this is not thought to be the main reason for the observed discrepancy.

The most likely change to the river isotope signature during and following mixture of the flow components would be fractionation due to evaporation leading to a heavier signature than predicted. This is opposite to what is observed, i.e. the real river chemograph is in fact lighter than predicted, therefore suggesting that either 1 and/or 3 needs to account for *more* than the apparent difference. If the end-member signatures are reasonable then, the most likely conclusion is that the predicted balance is biased toward an overestimation of isotopically heavy rainfall input that is volumetrically balanced by an underestimation of lighter snow and ice components. There are various lines of evidence to support this hypothesis.

For the first run of the UBC model, basin-wide snowpack was modelled as having almost completely disappeared at the end of both years and not supplying much water to river flow. This does not seem likely, as both of these years had a relatively deep snow pack and it is known (from personal field observations) that a large proportion of the snowpack remained at the end of each year. In addition, the specific yield for a gauged headwater basin of 4 km^2 glacier cover was calculated to be 5.5 mm/d for the relatively rain free month of August of 1996. At the same time, the combined specific yield for modelled snow and ice in the entire Bow Valley was almost 50% lower. This simple test suggests that glacial input to the river system was significantly underestimated in this calibration of the UBCWM. If snow and ice have been underestimated then what mechanism within the model has allowed too much rain to reach the river?

In Figure 3, it is apparent that the observed hydrograph is generally higher than the model's during late summer and it is only during rain events that the two sometimes converge. This suggests that the model is routing rain to the channel too quickly. This could also explain why the heaviest point in the modelled chemograph is one month ahead of that observed in the river for both years (Figures 5 and 6). Furthermore, the precipitation records from Castle Mountain indicate that the summer of 1997 had considerably more rainfall than that of 1996 and this is the only period where the observed chemograph lies outside one modelled standard deviation. If the model is indeed routing rain to the channel too quickly then there would be less opportunity for loss of this component due to evaporation, thus explaining why there could be too much rain in the balance. Alternatively, there could be a slight overestimation of the total rainfall entering the basin and this could be the result of using only one precipitation gauge plus a simple orographic enhancement factor to characterise rainfall for the entire basin.

It should be noted, however, that these differences between the observed and modelled river chemograph are quite minor compared to the differences between end-member component signatures. This suggests that these calibrations of the UBC model for 1996 and 1997 may actually provide a reasonable breakdown of the hydrograph components with a slight error in the routing algorithm/parameter selection or orographic enhancement function.

Isotopic Model Optimisation, UBC Model Run 2

Combining the dynamic isotope signatures with the first statistically optimised continuous UBCWM run from 1996 to 1999 did not provide favourable results (Figure 7) despite a reasonable r^2 of 0.83. This exemplifies the difficulty of calibrating a model accurately over a time series for years of very differing hydrological character. The chemograph of Figure 7 is on average 0.7 $^o/_{oo}$ too heavy, fluctuates markedly and is frequently outside the standard deviation range. These observations suggest that there was too much rain in the balance and that the modelled response was too rapid. After increasing the basin lapse rate and storage volumes in the model manually, the model was run again and tested in the same way. The coefficient of determination increased from 0.83 to 0.88 and the chemograph improved slightly (Figure 8). The difference between modelled and observed chemographs dropped to below 0.5 $^o/_{oo}$ but was still too heavy and variable. After further model runs and optimisation, no more improvements in both r^2 and isotope chemograph could be achieved. It may have been possible to improve the coefficient of determination with further manipulation but it is thought that this would have reduced the accuracy of the hydrological balance and therefore the modelled isotope chemograph.
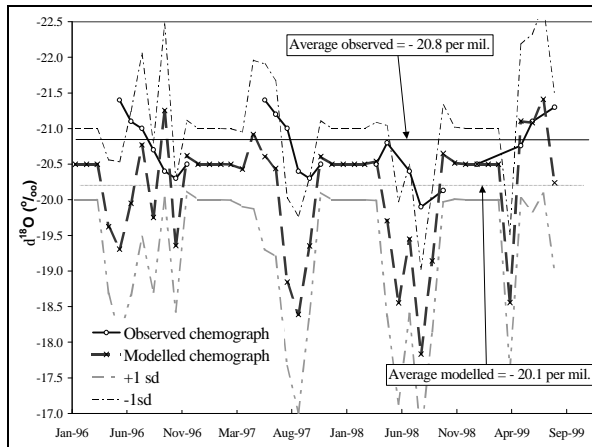

Figure 7. Aggregated observed and modelled $\delta^{18}O$ river signature for the Bow at Banff, 1996 – 1999 (continuous time series with dynamic end-member signatures).

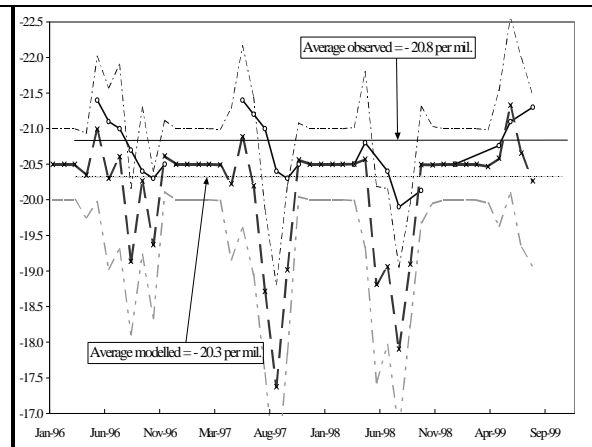Figure 8. Aggregated observed and modelled $\delta^{18}O$ river signature for the Bow at Banff, 1996 – 1999 (following recalibration).

CONCLUDING REMARKS

This paper has provided valuable insights in two areas:
1. A methodology for hydrological model evaluation and optimisation using oxygen isotope tracers been demonstrated;
2. Some of the potential problems modelling hydrological processes in mountainous environments over inter annual time series containing years of very different hydrological character have been illustrated.

From the first run of the UBC model from 1996 to 1997, it was shown that despite a reasonable statistical fit between observed and modelled data, the predicted hydrological balance was probably in error. The main cause of this error was thought likely to be a volumetric over-estimation of rainfall due to either:
a. an incorrect flow routing parameter and a commensurate underestimation of the loss of the rainfall component due to evapotranspiration or
b. an error in the orographic enhancement function.
Furthermore, in the cases demonstrated here, it is believed that too much rainfall was allowed into the balance for the following reasons:
a. the snowmelt contribution was under-estimated as a result of the total basin snowpack being under-estimated and therefore melting out too quickly and

b. glacial melt contribution during late summer months was significantly underestimated due to gross simplification of the glacial melt and storage processes within model algorithms.

The paper has therefore demonstrated that hydrological models can be evaluated and potentially optimised using oxygen isotope data taken from end-member hydrological components and the river being modelled. This kind of evaluation can provide a greater insight into potential errors with model routing and parameter value selection than a simple statistical test of the overall fit between observed and modelled hydrographs. Even a simple approach such as using long term averages of conservative stable isotope signatures of key flow components can be robust and produce useful results. A more accurate approach is to consider the spatio-temporal variations in these signatures but this may provide only a minimal improvement in the modelled chemograph for the considerable effort involved.

Although the method of this test has been manually intensive and costly, it may sometimes be useful to pursue similar forms of model validation in cases of long term water resource forecasting to assess the effect of climate and/or land cover change. In such studies, it is essential to start off with an accurate estimation of the hydrological balance for current or previous conditions. If the modelled balance is in error during calibration then it would very likely become worse the further into the future the prediction.

ACKNOWLEDGEMENTS

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