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A groundwater separation study in boreal wetland terrain: The WATFLOOD hydrological model compared with stable isotope tracers

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Monitoring of stable water isotopes (^{18}O and ^{2}H) in precipitation and surface waters in the Mackenzie River basin of northern Canada has created new opportunities for researchers to study the complex hydrology and hydroclimatology of this remote region [1]. A number of prior studies have used stable isotope data to investigate aspects of the hydrological regime of the wetland-dominated terrain near Fort Simpson, Northwest Territories, Canada [2, 3]. The present paper compares estimates of groundwater contributions to streamflow derived using the WATFLOOD distributed hydrological model, equipped with a new water isotope tracer module, with the results of conventional isotope hydrograph separation [4] for five wetland-dominated catchments along the lower Liard River. The comparison reveals highly promising agreement, verifying that the hydrological model is simulating groundwater flow contributions to total streamflow with reasonable fidelity, especially during the crucial snowmelt period. Sensitivity analysis of the WATFLOOD simulations also reveals intriguing features about runoff generation from channelized fens, which may contribute less to streamflow than previously thought.

Keywords: Hydrograph separation; Hydrological modeling; Isotopes; Oxygen-18; Deuterium; Model evaluation; Natural abundances

1. Introduction

A need exists to improve the scientific understanding of hydrological flow paths, sources, and cycling within natural environments, not only to determine the potential impacts of contaminants on water supplies and develop appropriate management practices, but also to understand

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the past climate history and predict potential impacts of climate change on water resources world-wide [5, 6]. Integral to the scientific understanding of the water cycle and desegregation of flow paths is the ability to accurately and precisely model the hydrologic cycle. There exists a multitude of hydrological models [7–9] that are commonly used tools for defining and assessing rainfall–runoff relationships, available in a wide range of complexities. These models range from catchment specific conceptual box-type models (reservoir models) [10], to more general variable source area models, such as Beven's TOPMODEL [11], to widely applicable, fully distributed (and more complex) HRV models [12, 13]. However, along with complexity come additional costs for data collection, model inputs, computational costs, and uncertainties. Often, the simplified conceptual models offer the greatest potential for development and application, particularly in catchments where physical parameters cannot be determined *a priori* as is required for physically based models [10]. It is no longer the case that increased complexity leads to increased accuracy. So the question then becomes: Which results are most representative of the observed environmental and physical flow systems being modelled given the uncertainties inherent in modelling [14–17]? There is an ever-growing need to establish an accurate, efficient and practical means of evaluating hydrological models, which can be used for any study area no matter how populated or remote. Over the past two decades stable water isotopes (deuterium and oxygen-18) have become increasingly popular tools for hydrological studies, attempting to improve the understanding of water sources, partitioning and cycling within watersheds [18–22]. It has been recognized that the incorporation of isotope data into hydrological models can serve to provide valuable insight into the inner workings of mesoscale watersheds, and that they may also provide an invaluable tool for model verification and internal testing of state variables [10, 20, 23–25].

Oxygen and hydrogen stable isotopes (^{18}O and ^{2}H) are ideal tracers of water sources because they are naturally occurring constituents of water molecules ($^1H^1H^{18}O$ and $^1H^2H^{16}O$); they behave conservatively, and often carry varied signatures for different contributions to runoff [6, 17, 26]. Stable water isotope ratios, δ^{18}O and δ^{2}H, can be used to determine the contributions of old and new water to a stream during periods of high runoff because rain or snowmelt (new water) triggering runoff is usually isotopically different from the water already in the catchment (old water) [6]. Given the systematic variations stable isotopes exhibit within the hydrological cycle as a result of fractionation effects accompanying phase changes and diffusive processes [27, 28], they can be used to ascertain the origin and/or historical flow path of the water sample. In this way, the contributing sources to total streamflow can be quantifiably segregated based on measured isotopic signatures, knowledge of the significantly contributing components (end-members) to streamflow, and a distinct isotopic signature for each end-member. Some key assumptions limiting the utilization of stable water isotopes for source separation include, (1) identification of two or three distinctive end-members, and the assumption that all other compartments are negligible contributors to streamflow and therefore will not alter the isotopic signature significantly; (2) the end-members are isotopically distinctive; (3) constant composition of each end-member; and (4) tracers are conservative [16, 20].

The rainfall-runoff process can be modelled using hydrological models [8], in which conservative tracers can be incorporated and used to disaggregate streamflow into its various origins and pathways. A common challenge with hydrological models is the issue of equifinality [29], where a number of equally appropriate stream flow simulations can be achieved using widely differing model parameters. The measurement of naturally occurring stable isotopes in streamflow can then provide a relatively simple and inexpensive verification tool for models through the constraining of the mass balance equation, hence reducing the degrees of freedom in parameter estimation. The objective of this paper is to validate groundwater discharge estimations made by the WATFLOOD hydrologic model for the Fort Simpson, Northwest Territories basin ($\sim$5000 km^2) by comparing modelled tracers to isotopically partitioned streamflows.

To the authors' knowledge, a study coupling analysis of stable water isotopes with a hydrologic model for the purposes of model verification in a mesoscale, remote, Northern basin has not yet been undertaken.

2. Study area

Field site investigations, daily discharge measurements and an isotopic study were conducted from 1997 to 1999 within the lower Liard River valley, in close proximity to the community of Fort Simpson, Northwest Territories (61°45'N; 121°14'W; figure 1), as part of the Mackenzie GEWEX Study (MAGS) [30, 31]. Within the lower Liard valley, there are five wetland-dominated mesoscale river basins; Jean-Marie River (1310 km^2), Martin River (2050 km^2), Birch River (542 km^2), Blackstone River (1390 km^2), and Scotty Creek (202 km^2).

The study area is characterized by meandering streams, discontinuous permafrost, and extensive peatlands (bogs and fens) [32]. The stratigraphy commonly consists of a thick accumulation of organic peat deposited over extensive areas of poorly drained lacustrine (silt and sand) sediments, which overlie poorly drained glacial deposits (till), below which lie clay deposits [33]. The topographic relief tends to increase towards the northwest area of the basin, with Martin River having the steepest gradient (0.7%). Scotty Creek, characterized by peat plateaus and flat oligotrophic bogs [3], has the shallowest relief (0.2% gradient). Table 1 shows

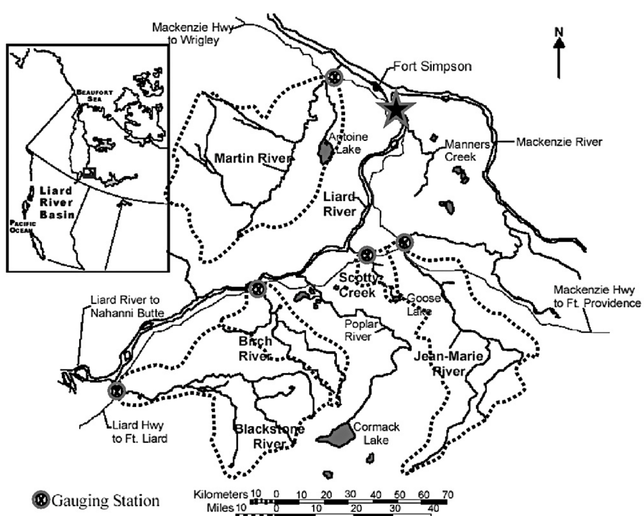

Figure 1. Map of Fort Simpson, NWT study area and basin delineation. The weather station is indicated by the star.

Table 1. Distribution of percent land coverage for the five catchments.

	Mixed/deciduous (%)	Conifer (%)	Transitional (%)	Wetland (%)	Water (%)	Impervious (%)
Jean-Marie River	29	23	32	14	1	1
Martin River	25	20	35	17	1	1
Birch River	29	8	36	25	1	1
Blackstone River	25	14	39	20	1	0
Scotty Creek	13	32	42	13	1	1

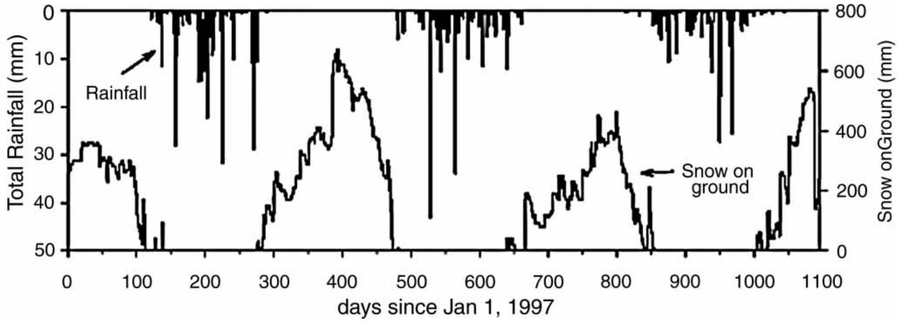

Figure 2. Recorded precipitation over the 1997–1999 study period.

the percent distribution amongst the five identified land cover classification from LANDSAT imagery for each catchment.

A summary of the recorded rainfall over the study period is presented in figure 2, with precipitation in the winter shown as snow water equivalent. Figure 2 shows that the percentage of rainfall from the end of summer 1997 and throughout 1998 was higher than normal, reflecting the increase in moisture sources during this El Niño year, also corresponding to warmer-than-normal air temperatures in 1998.

3. Methods

3.1 *Field data*

During the study period, streamflow and snow samples were taken periodically, 10 to 12 times per sampling season (April to August) from the five catchments and analysed at the University of Waterloo Environmental Isotope Laboratory for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios. The latter are expressed in the conventional format as δ values relative to Vienna Standard Mean Ocean Water (VSMOW), such that $\delta_{water} = (R_{water}/R_{\text{VSMOW}} - 1)\ 1000‰$, where R is $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in sample and standard [34]. Maximum analytical uncertainties of δ values are $\pm 0.1‰$ for $\delta^{18}O$ and $\pm 2‰$ for $\delta^{2}H$ [4]. The contributions from the various end-member components to the overall isotopic composition of the streamflow sampled can be visually distinguished when samples are plotted in $\delta^{2}H$-$\delta^{18}O$ space. Since sampling of streamflow could only occur periodically throughout the study period, isotopic values of streamflow were interpolated to daily values weighted according to the daily volumetric discharge. The result was a time-series partitioning ($\delta^{18}O$ and $\delta^{2}H$ measurements corresponding to a given sampling day) of streamflow into snowmelt, surface water, and groundwater components [4].

Precipitation data was obtained from a single rain gauge servicing all five catchments, located at the Fort Simpson airport Class-A synoptic weather station. Air temperature data was collected from the Fort Simpson Airport and several other sampling points scattered throughout the study area. The Water Survey of Canada maintains daily discharge measurements of the Liard River and near the outlet of the five catchments. Extensive snow course surveys, expressed as snow water equivalent (SWE) in millimetres, and observed land cover types for weighted adjustment factors were recorded for each of the five catchments from March 1997–1999 when snow thickness was at a maximum [35].

3.2 *Isotope mixing model*

Groundwater in storage typically has a relatively constant isotopic signature over time, reflecting the long-term precipitation average due to recharge and minimal evaporative influence [27]. Throughout the cold season in northern basins with discontinuous permafrost, streamflow isotopic composition is dominated by groundwater. During the spring, isotopically depleted snowmelt runoff mixes with the enriched groundwater in the stream, resulting in a depletion of the ice-on isotopic signal. As the freshet period ends, summer streamflows become enriched due to higher rates of evaporation causing preferential loss of the lighter isotope, resulting in a progressive enrichment of the streamflow isotopic signal throughout the summer. Major variations in streamflow isotopic composition are therefore controlled by the balance between snowmelt and groundwater during the spring freshet period, and by the balance between surface water and groundwater during late fall and winter for such Northern basins [4]. Therefore in northern environments, δ^{18}O and δ^{2}H isotopic compositions in streamflow are seasonally influenced by the mixing of three inputs that are commonly isotopically distinct; primarily snowmelt, surface water, and groundwater. This allows for the basin streamflow to be separated into its constituent components using the classical two-component mixing model [5, 22, 36, 37]. The mixing ratio between source water components in streamflow is determined using mass and isotope balance calculations. Assuming instantaneous and complete mixing of all components [20], total streamflow Q during the freshet period is the sum of direct snowmelt runoff D, groundwater inflow R_{GW}, surface water inflow (from stormflow) R_{SW}, and direct channel precipitation P:

$$Q = D + R_{GW} + R_{SW} + P \tag{1}$$

$$\delta_Q Q = \delta_D D + \delta_{GW} R_{GW} + \delta_{SW} R_{SW} + \delta_P P, \tag{2}$$

where δ values refer to the isotopic composition of the respective components.

For long time sequences and smaller basins, the contribution to streamflow by direct precipitation can be assumed negligible, as most precipitation recharges groundwater or becomes surface runoff. The above equations are then simplified to:

$$Q = D + R_{GW} + R_{SW} \tag{3}$$

$$\delta_Q Q = \delta_D D + \delta_{GW} R_{GW} + \delta_{SW} R_{SW}. \tag{4}$$

For the warm-season, post freshet period, the absence of snowmelt further simplifies the equations, and total streamflow is given by:

$$R = R_{GW} + R_{SW} \tag{5}$$

$$\delta_R R = \delta_{GW} R_{GW} + \delta_{SW} R_{SW}. \tag{6}$$

During the ice-free summer and fall periods, δ_RR becomes the isotopic composition of baseflow (the most enriched composition of the streamflow). During this period, δ_R consists of a greater mixture of evaporatively-enriched surface water and rain relative to depleted groundwater (i.e., $\delta_R \rightarrow \delta_{SW}$).

Figure 3 shows a schematic representation of the isotopic partitioning of streamflow using the two-component mixing model approach [4].

The separation of total streamflow Q into newer, event based versus older baseflow components can be achieved by segregating direct snowmelt, D from ice-off baseflow, R as

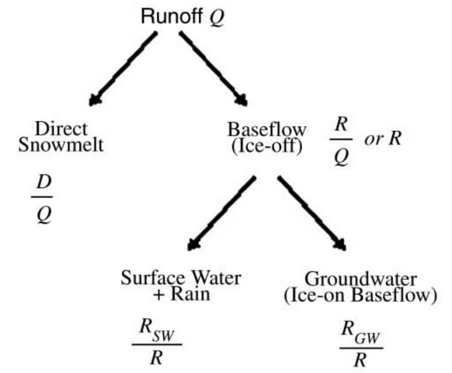

Figure 3. Schematic representation of isotopic streamflow partitioning.

a proportion of total streamflow, Q. By substituting equation (5) into equation (3), and normalizing by total streamflow:

$$1 = \frac{D}{Q} + \frac{R}{Q}, \tag{7}$$

where isotopic contributions of snowmelt and baseflow during the freshet recession period can be defined as,

$$\frac{D}{Q} \approx \frac{\delta_Q - \delta_R}{\delta_D - \delta_R} \tag{8}$$

$$\frac{R}{Q} \approx \frac{\delta_Q - \delta_D}{\delta_R - \delta_D} \approx 1 - \frac{D}{Q}. \tag{9}$$

For the post-freshet period (summer and fall), baseflow can be further partitioned from equations (8) and (9) into contributions from event water as surface runoff or rain, R_{SW} and groundwater:

$$\frac{R_{SW}}{R} = \frac{\delta_R - \delta_{GW}}{\delta_{SW} - \delta_{GW}} \tag{10}$$

$$\frac{R_{GW}}{R} = \frac{\delta_R - \delta_{SW}}{\delta_{GW} - \delta_{SW}} \approx 1 - \frac{R_{sw}}{R}. \tag{11}$$

Winter flows would have an isotopic composition near to groundwater, such that $R_{SW} \to 0$ and $R \approx R_{GW}$ during ice-on (winter) low-flow.

3.3 *WATFLOOD hydrological model*

The modelling platform used in this study is the WATFLOOD hydrological model (http://www.watflood.ca). It is a semi-distributed, mesoscale hydrologic model for watersheds having response times larger than 1 hour, and can be used to model both large and small catchments ranging from 1,700,000 km^2 for the Mackenzie River basin, to 20 km^2 for watersheds in the foothills of the Rocky Mountains near Hinton, Alberta, Canada. The model was originally developed as an event-based model [38], however, it has been adapted for use in continuous simulation of long time sequences, including applications in climate change studies and numerical weather prediction [39]. The model incorporates vertical and horizontal

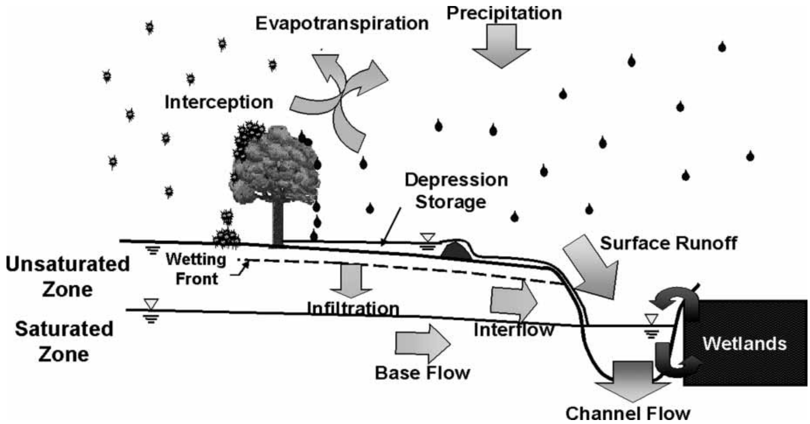

Figure 4. Graphical representation of WATFLOOD's hydrology.

water budgets that include surface water, interflow and groundwater components, wetland hydrology, wetland–channel interaction, and soil moisture, all of which contribute to the total streamflow (figure 4). WATFLOOD uses grouped response units (GRUs) as its basic computational unit, which are designed to provide a distributed approach to modelling while keeping the computational efficiency very high. An element (or grid) is composed of many GRUs, one GRU for each hydrologically significant land cover type, and the hydrological responses from all GRUs in an element are summed to give a total hydrological response (figure 5). With the GRU approach, land cover may be easily modified, the model re-run, and the impact or sensitivity to land-use change evaluated [40].

The model is designed to make optimal use of remotely sensed data, such as topography from digital elevation models (DEMs), land-use, or land-cover data from LANDSAT imagery, and

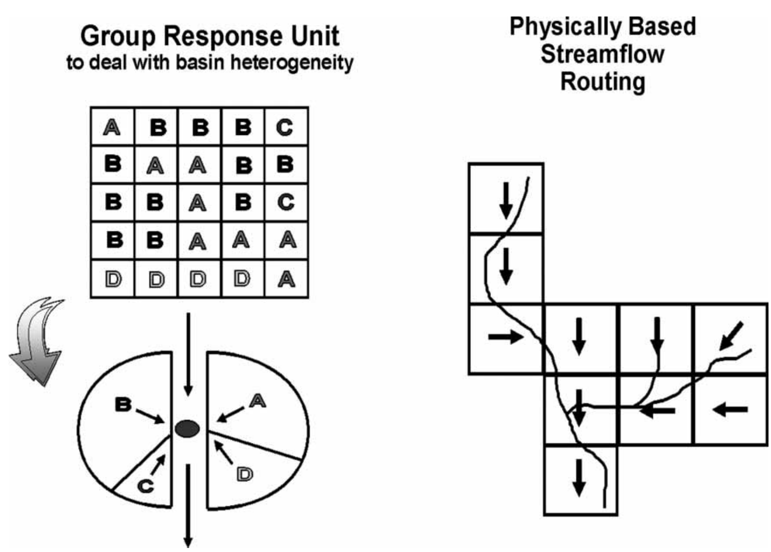

Figure 5. WATFLOOD runoff from each GRU is summed to give total grid response.

precipitation estimates from radar. Minimal meteorological inputs for WATFLOOD include temperature data, rain gauge data, measured streamflow, and snow course data. In the absence of temperature data, evaporation data from pan measurements can be used to estimate evaporation. WATFLOOD can also use to its advantage snow course data, radiation data (to estimate evaporation and snowmelt), radar data, snow gauge data, recharge flux estimates, and reservoir release data for rivers that are controlled.

3.4 *Tracer module*

A conservative tracer module has been integrated as a stand-alone subset of the WATFLOOD model. Conservative tracers are used to track water through the model by quantifying and segregating the various contributions to the total streamflow at the point of generation. Baseflow separation is accomplished using simplified storage routing of groundwater through the subsurface and into the stream. A specified mass of tracer is added to the stream from the incoming groundwater flow:

$$MassIN(n) = Conc(n) \times qlz(n) \times t, \tag{12}$$

where $Conc(n)$ [kg/m^3] is the concentration of tracer existing in a given grid cell, $qlz(n)$ is the baseflow entering the stream for a given grid cell [m^3/s], and t is the time step in seconds.

Upon reaching the stream, a mass balance is performed to determine the amount of tracer (groundwater) stored in the stream:

$$S_2(n) = S_1(n) + \frac{[Inflow(n) - Outflow(n)]}{2}, \tag{13}$$

where $S_1(n)$ and $S_2(n)$ are the mass storages of tracer for each grid cell (n) in units of mass at the beginning and end of the time step respectively, $Inflow(n)$ represents the incoming tracer mass to the grid cell from upstream flow, and $Outflow(n)$ represents the tracer mass leaving the grid cell through the stream (downstream flow). Thus, concentration of tracer in the stream may be calculated as a percentage of tracer mass being stored:

$$Conc(n) = \frac{S_2(n)}{storage(n)}, \tag{14}$$

where $storage(n)$ is the total volume of water in the channel [m^3]. As the isotope mixing model assumes, instant mixing of the tracer in each grid cell is performed.

Finally, the mass of tracer entering the stream, less the evaporative loss of tracer, is calculated yielding a separation of groundwater from total streamflow:

$$MassOUT(n) = Conc(n) \times Q_{stream}(n) \times t - Conc(n) \times Q_{evap}(n) \times t, \tag{15}$$

where $Q_{stream}(n)$ is the total streamflow for the grid cell in m^3/s, and $Q_{evap}(n)$ is the evaporative flux from the grid cell in m^3/s. The evaporative flux is subtracted from the mass of tracer in the stream in order to account for evaporative water loss from the stream that would otherwise artificially concentrate tracer due to the decrease in water volume and conservation of mass.

Once the mass of tracer in the stream has been calculated for a given grid cell, this mass is transferred to the next grid cell as the "mass in", and the whole process repeats for equations (1) through (5):

$$MassOUT(n) = MassIN(n + 1). \tag{16}$$

Similarly, surface flow, interflow, and melt components can be segregated from the total streamflow, as well as flow from particular land covers and areal regions of the basin. Since the initial concentrations of tracer (isotopes) in each compartment (end-member) are not easily obtained, initialisation of concentration is not required given a sufficient model spin-up period.

4. Results

Total annual discharge and partitioned groundwater contributions were calculated in hourly timesteps for the spring and summer periods of 1997 to 1999. Continuous simulation was not possible due to limited data availability, so model initial conditions were re-established every spring using the detailed snow-surveys.

A comparison of the isotopically partitioned streamflows was made to the modelled tracer results from WATFLOOD. By comparison, it is possible to verify that the model is correctly estimating contributions to groundwater stores. When modelled results do not match isotopic flow separations, it is assumed the model is not correctly estimating the groundwater flowpath. Quality and accuracy of the modelled results is assessed by two criteria: (1) the measure of fit between the modelled and measured streamflow, and (2) the relative proportioning of modelled groundwater matches isotopically separated groundwater. For the first criteria, Nash-Sutcliffe goodness of fit (R^2) and deviation of runoff volumes (D_v) were the primary statistics used to determine how well the modelled flows simulate the measured flows, along with visual inspection of the catchments response to events from the shape and timing of the hydrographs. A value of one indicates a perfect fit between simulated and measured flows. A Nash-Sutcliffe value of zero means the simulated hydrograph is predicting no better than the average flow for the entire period. Negative values are possible and indicate that the simulations are worse than using the mean streamflow value as an estimate of simulated flow rates for that time period. The deviation of runoff volume statistic (D_v) is also a goodness-of-fit test that statistically compares measured and computed volumes of discharge during an event, providing information on how well the overall water balance is being modelled. A value of zero indicates no difference between measured and simulated volumes. A positive D_v indicates under-estimation of simulated volumes (missing source), whereas a negative D_v indicates over-estimation of simulated volumes (missing sink).

For the second criteria, proportionality plots comparing isotopically separated groundwater normalised by measured streamflow on the x-axis, versus modelled groundwater normalised by simulated streamflow on the y-axis were used. Normalising the groundwater estimates by total streamflow allows for a comparison of groundwater volumes, irrespective of errors in estimation of total streamflow. As such, all points should plot close to the 45-degree line (slope of one), indicating perfect proportionality between modelled and isotopically separated flows.

The WATFLOOD hydrologic model was run using the wetland hydrology option [41] on each of the five catchments from April to August 1997 to 1999. During this study, it was found that use of percent wetland cover as ascertained from LANDSAT imagery resulted in an over-estimation of wetland coverage. This finding has been supported by knowledge of the study site, land cover surveys, and recent remote sensing studies of Scotty Creek [42, 43]. It has substantiated the belief that although extensive wetland coverage is apparent throughout the five catchments, not all of these wetlands may be hydraulically connected to the channel via a direct pathway. This is not only indicated in the simulation results, but is supported by numerous historical field site investigations showing that many of the wetlands in areas of low-relief topography have no apparent connection to a channel [5, 32, 42]. As such, the treatment of wetlands in the WATFLOOD model was altered to incorporate an additional land cover classification, "connected wetlands" that represents the channelised fens characterised by previous workers [42], to distinguish from the LANDSAT identified wetland class that includes both fens and bogs as generic wetland coverage. This new land classification is a parameterised fraction of the existing wetland class, determined by model calibration. The results of this calibration indicate that approximately ten percent of the Fort Simpson wetlands are hydraulically connected to a channel (i.e., channel fens). This is not consistent with reports that channel fens were shown to occupy about two-thirds of the overall wetland classes [42]. Clearly, more information on the classification and understanding of the extent and function of these fens is required.

Given the assumed ten percent wetland hydraulic connectivity, simulations for the five catchments from April to August 1997 through to 1999 were completed and the results are presented on figures 6, 7, and 8. All statistical results for these simulations

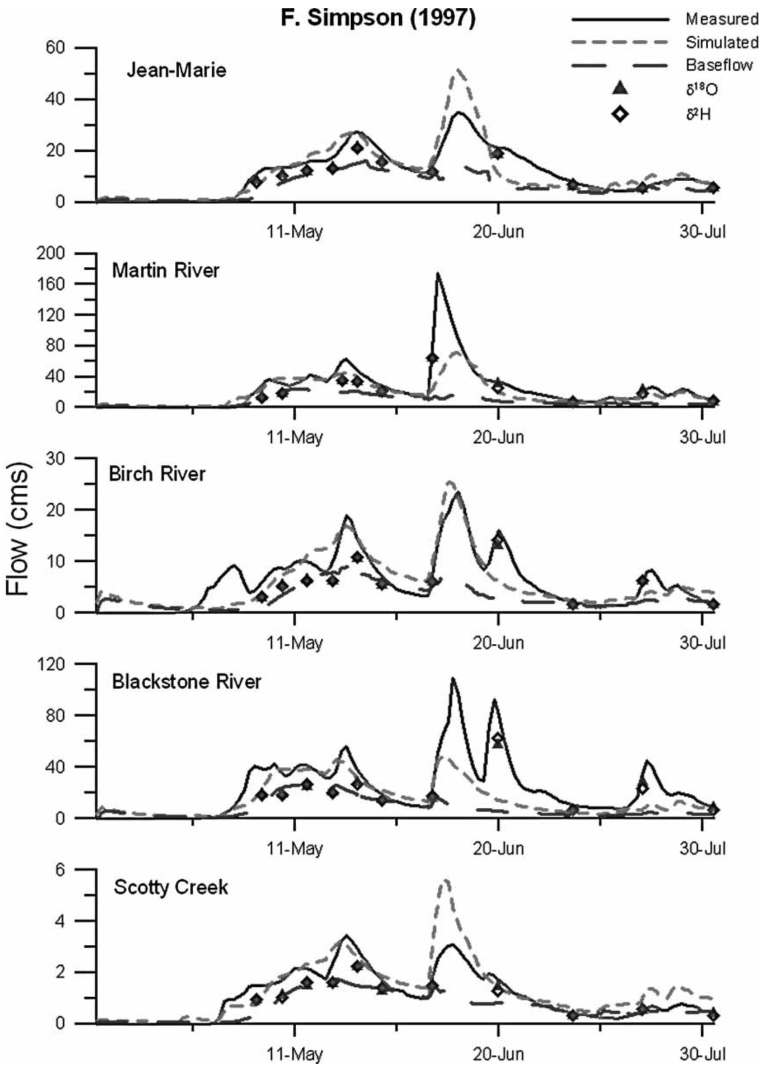

Figure 6. 1997 WATFLOOD simulation results for the Fort Simpson catchments.

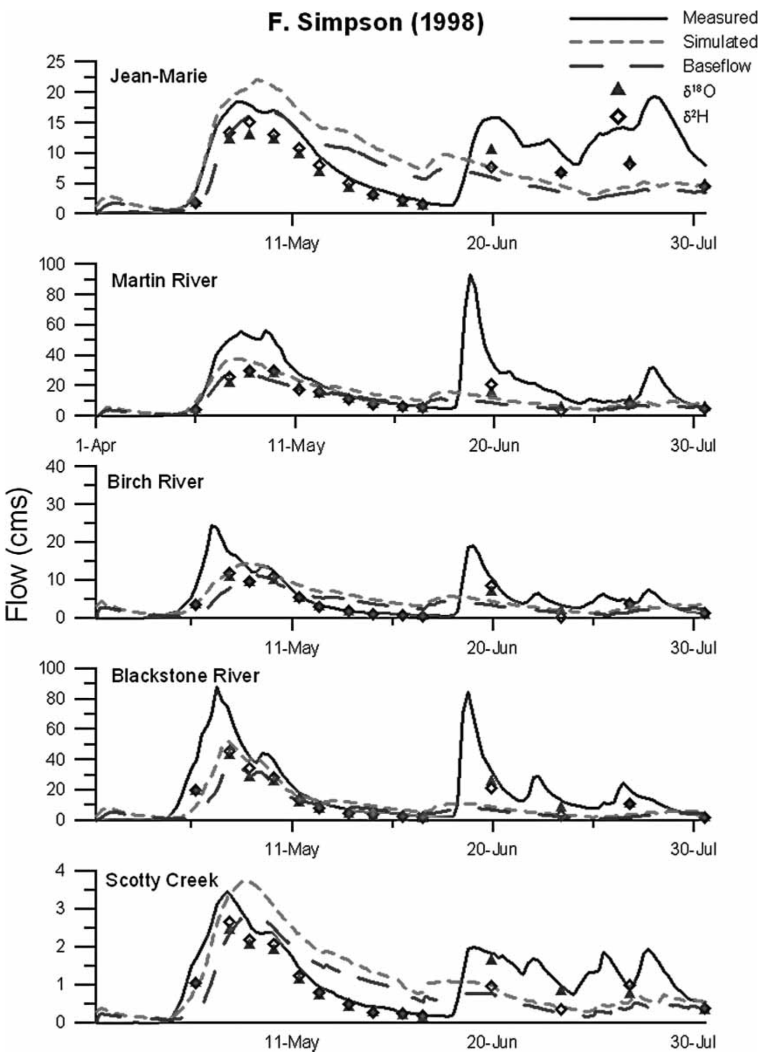

Figure 7. 1998 WATFLOOD simulation results for the Fort Simpson catchments.

have been provided in table 2. Groundwater proportionality plots are provided in Appendix A.

It is important to note the scarcity of meteorological inputs, and the resulting effect on the modelled hydrographs, namely several summer rain events were missed throughout the study period. This is notable in June of 1997, where a significant rainfall event was observed that resulted in significant event hydrographs in all five catchments. However, the Fort Simpson rain gauge did not capture this event, and therefore it was not simulated by the model. According to equation (5), which describes the flow contributions during the post-freshet period, neglecting rainfall (and therefore surface runoff) results in total streamflow equal to baseflow contribution alone ($R \approx R_{GW}$). This phenomenon can be observed during the summer months of the three study years due to unrecorded precipitation events missed by the rain gauge.

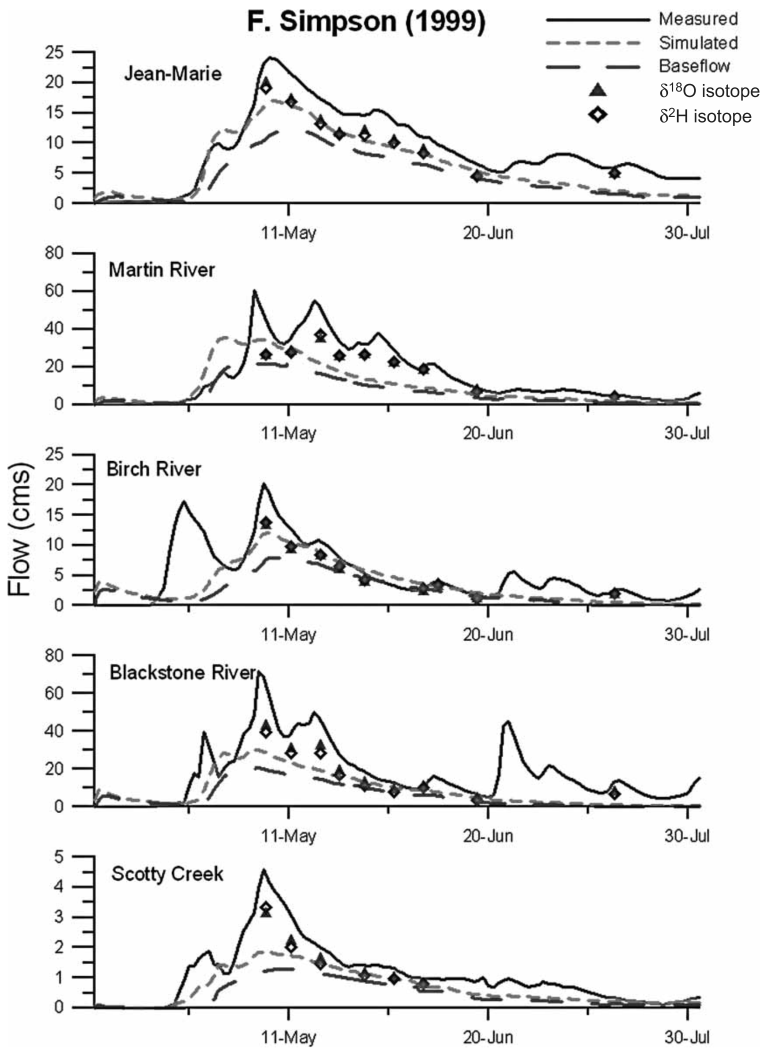

Figure 8. 1999 WATFLOOD simulation results for the Fort Simpson catchments.

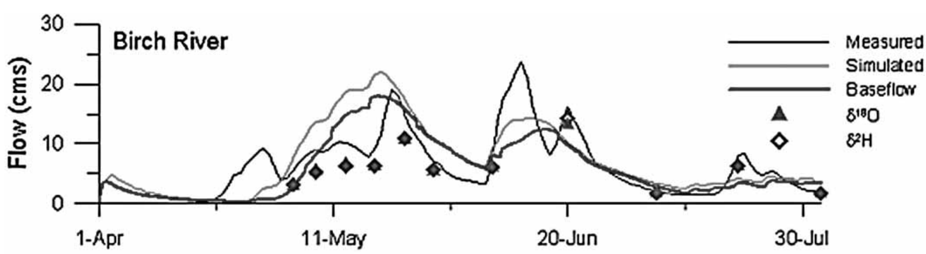

Figure 9.

Table 2. Statistical results from the WATFLOOD simulations.

Year	Basin	Slope of proportionality plot	Nash	%Dv
1997	Jean-Marie	0.735	0.723	2.616
	Martin	0.653	0.569	−21.149
	Birch	0.739	0.702	−1.167
	Blackstone	0.798	0.387	−33.462
	Scotty	0.735	0.624	24.328
	Average	0.732	0.60	−5.77
1998	Jean-Marie	1.022	−0.074	−8.079
	Martin	0.982	0.32	−32.255
	Birch	0.935	0.389	−9.865
	Blackstone	1.157	0.339	−40.466
	Scotty	0.981	0.213	0.473
	Average	1.015	0.24	−18.04
1999	Jean-Marie	0.990	0.698	−28.792
	Martin	0.905	0.47	−33.055
	Birch	0.883	0.338	−29.916
	Blackstone	0.958	0.2041	−50.052
	Scotty	1.010	0.549	−38.435
	Average	0.949	0.45	−36.05
Desired Outcome		1	1	0

5. Discussion

By inspection, the 1997 hydrographs (figure 6) show reasonable fit of simulated to measured flows in each of the five catchments based on hydrologic response to events (rising and falling of the hydrograph) and timing. In all catchments, WATFLOOD appears to over-estimate streamflow during the freshet period, most notably for the Birch and Blackstone Rivers (wetland dominated catchments). Scotty Creek, Jean Marie, and Martin river catchments all exhibited similar behaviour during calibration, indicating they have similar hydrologic responses. The Birch and Blackstone Rivers, however, indicated different hydrologic responses from the other catchments, most likely attributed to the responsive wetland hydrology dominating these catchments. Overall, the 1997 snowmelt period was well simulated, exhibiting comparable melting trends with observed streamflow increases, and subsequent decreases. The Nash-Sutcliffe coefficient varied from a worst-fit simulation of 0.38 for Blackstone River to the best fit on Jean-Marie River at 0.72 (table 2). The accuracy of fit for the catchments was also captured by the D_v, varying from 33% under-estimation of runoff volume for Blackstone River, to only a 2% deviation for Jean-Marie River. The proportionality plots indicate an overall under-estimation of groundwater volume by WATFLOOD in 1997, varying from a slope of 0.65 (Martin River) to 0.8 (Blackstone River). It is interesting to note that despite difficulties simulating total streamflow in the Blackstone River catchment, groundwater was well apportioned.

The 1998 hydrographs (figure 7) exhibit a substantially worse fit of simulated to observed streamflow even by first inspection, noticeably during the snowmelt (freshet) period. In all catchments, WATFLOOD simulations prolonged the duration of the melt period, leading to high-volume, prolonged recession melt hydrographs. This result is attributed to the onset of the El Niño event, which led to warmer and wetter conditions occurring earlier in the spring than normal. Given that the same parameter set was used in WATFLOOD for all years, and that the simulations did not incorporate radiation data, the model could not accurately forecast this earlier and quicker melt event. Previous work has shown that the addition of radiation data to the WATFLOOD model can largely correct these discrepancies; however, radiation data was not available for this study [32]. Resulting from the poorly modelled freshet period, the Nash-Sutcliffe coefficients were generally quite low (indicating poor fit), varying from −0.07 (Jean-Marie River) to 0.38 (Blackstone River), interestingly in direct contrast with the 1997 results. The D_v varied from 40% under-estimation of runoff volume (Blackstone River), to a negligible over-estimation (0.5%) of runoff volume in Scotty Creek. The proportionality plots indicate that groundwater was over-estimated on the Blackstone River, with a slope of 1.16, whereas the groundwater was most correctly apportioned on the Jean-Marie River (slope of 1.022). All other catchments under-estimated streamflow contributions from groundwater. The 1998 results illustrate that the Blackstone and Birch Rivers appear to model the El Niño freshet period more accurately than the other catchments (supported by their higher R^2 values), perhaps attributable to their wetland-dominated coverage, which would be less responsive to early radiation inputs and would naturally dampen excess prolonging of the recession curves. Some of the catchments, like Scotty Creek, exhibited poor fit of simulated streamflow but overall, resulted in a good water balance. This is likely more to the opportune cancellation of errors, where the prolonged recession curve volume appears to have closely estimated the volume of the missed rain event.

By initial inspection, the 1999 hydrographs (figure 8) exhibit improved fit over the 1998 simulations in each of the five catchments. The results correlate more closely with 1997 simulations, supporting evidence that the erroneous streamflow simulations in 1998 are in some way attributable to the El Niño event. In 1999, the freshet period once again occurred during the expected, normal late spring season, and at a slower rate than in 1998. However, in 1999, some earlier small precipitation events (likely a carryover of moisture from the El Niño event) occurred and were once again missed by the rain gauge, leading to poor fit (low R^2) of simulated to observed flows throughout the summer periods, and an overall under-estimation of runoff volumes (negative D_v's). The Nash-Sutcliffe coefficient varied from 0.2 for the Blackstone River to 0.55 for Scotty Creek. The D_v was consistently under-estimated due to the missed rain events, varying from −50% on the Blackstone River to −28% on the Jean-Marie River. The proportionality plots indicate, once again, a general under-estimation of groundwater contribution by WATFLOOD. The Birch River simulation under-estimated groundwater contribution most significantly with a slope of 0.88. Jean-Marie River and Scotty Creek correctly apportioned groundwater with slopes of 0.99 and 1.01, respectively. The 1999 results again point to problems with the Blackstone River simulations, perhaps resulting from poorly estimated wetland connectivity (fen channelisation).

Overall, the groundwater proportioning for 1997 through to 1999 was reasonable despite some obvious discrepancies between simulated and measured flows (particularly missed summer events). In all cases, the slopes of the proportionality plots were close to one, but in general less, indicating the amount of groundwater WATFLOOD apportions is slightly less than what is observed from the isotope data. One apparent trend from both the WATFLOOD and isotopic separations was that all five catchments are groundwater-dominated, with groundwater contributions being upwards of 60 to 95% of total streamflow. It is noted that the proportionality plots all indicate one or two measurements where modelled groundwater from WATFLOOD is significantly lower than isotopically separated groundwater. These points occurred in all catchments and correlate to the beginning of the freshet period on the rising limb of the melt hydrograph. These anomalous points can, at least in part, be explained by the numerical smoothing that results from the averaging of modelled hourly groundwater flows to obtain daily flows that correlate with the daily average isotope estimates [4]. This smoothing results in a less steep and less drastic gradient on the rising limb, resulting in lower groundwater flow estimates during the early rising limb period of a given event.

6. Conclusions

Simulated groundwater contributions from WATFLOOD prove to be representative of the isotopically-separated groundwater volumes. In addition, both methods indicate that runoff generation in all five Fort Simpson catchments are strongly groundwater-dominated, ranging from 60 to 95 percent groundwater contribution to total streamflow. It was not unexpected that the catchments would be groundwater-dominated, however the percent groundwater contribution was higher than what might have been expected in a region of discontinuous permafrost [44]. In future northern studies the significance of groundwater contributions to streamflow should not be under-estimated. Further studies encompassing more northern climates where glacial melt may also be a contributing end-member should be under taken to quantify glacier contributions to, and effects on, total streamflow as part of climate change research studies.

The incorporation of the isotope data into the hydrological model was consistent with other hydrological studies in highlighting the importance of understanding the function of channelised fens in controlling the runoff response in this hydrological regime. Modification of the model to incorporate a percent connected-wetland coverage (i.e., fen) accounting for low relief, low-hydraulic gradient wetlands that do not directly and immediately interact with streamflows was essential to obtain reasonable simulation results. For the Fort Simpson catchments, it was found (by calibration) that approximately 10 percent of total wetland coverage appears to interact with the streamflows directly. Some catchments however, such as Blackstone River, appear to deviate from this. It is recommended that wetland connectivity be determined on a per catchment basis either as a calibrated parameter, or as a function of either topographic relief that could identify low-lying areas separated from any channels, or LANDSAT imagery that could possibly distinguish and quantify riparian zones (vegetation cover) lining the channels. Often digital elevation data does not have sufficient resolution to map wetland hydraulic gradients. Preliminary investigations into the usefulness of LANDSAT and higher-resolution satellite imagery such as Ikonos for determining connectivity and land-cover distributions are encouraging [43]. Further investigation of how to account for the apparent variability of wetland connectivity within the model is clearly required.

The incorporation of stable isotope tracers into the WATFLOOD model has shown that it is possible to improve our understanding of the hydrological function of a basin through a combination of experiments, observations and models. Moreover, the incorporation of the stable isotope tracers has shown that the WATFLOOD model, although crude in its methods of groundwater estimation relative to full physically based models, appears to reasonably simulate groundwater contribution to total streamflow for the Fort Simpson catchments. By reducing the model's degrees of freedom through isotopic measurements, important conceptualisation of the behaviour of the catchment can be established and simulated. As with all modelling exercises, there are inherent uncertainties; nevertheless, it is clear that the incorporation of isotopes into hydrological models can serve to constrain these uncertainties.

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References

[1] J.J. Gibson, P. Aggarwal, J. Hogan, C. Kendall, L. Martinelli, W. Stichler, D. Rank, I. Goni, M. Choudhry, J. Gat, S. Bhattacharya, A. Sugimoto, B. Fekete, A. Pietroniro, T. Maurer, H. Panarello, D. Stone, P. Seyler, L.M. Bourgoin, A. Herczeg. Isotope studies in large river basins: A new global research focus. *EOS*, **83**, ?? (2002).

[2] J.J. Gibson, T.D. Prowse, T.W.D. Edwards. Development and validation of an isotopic method for estimating lake evaporation. *Hydrol. Processes*, **10**, 1369 (1996).
[3] M. Hayashi, W.L. Quinton, A. Pietroniro, J.J. Gibson. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. *J.Hydrol.*, in press (2004).
[4] N.A. St. Amour, J.J. Gibson, T.W.D. Edwards, T.D. Prowse, A. Pietroniro. Isotopic time-series partitioning of streamflow components in wetland-dominated catchments, lower Liard Basin, Northwest Territories, Canada. In *Hydrol. Processes* IAEA Special Issue in press (2005).
[5] International Atomic Energy Agency. Water & Environment Newsletter, Issue 17 (2003).
[6] C. Kendall, M.G. Sklash, T.D. Bullen. Isotope tracers of water and solute sources in catchments. In *Solute Modelling in Catchment Systems*, S.T. Trudgill (Ed.), John Wiley & Sons, Chichester (1995).
[7] V. Singh (Ed.). *Applied Modelling in Catchment Hydrology*, Water Resources Publications, Highlands Ranch, Colorado (1981).
[8] V. Singh (Ed.). *Computer Models of Watershed Hydrology*, Water Resources Publications, Highlands Ranch, Colorado (1995).
[9] V. Singh, D.K. Frevert (Eds.). *Mathematical Models of Large Watershed Hydrology*, Water Resources Publications, Highlands Ranch, Colorado (2002).
[10] J. Siebert, J.J. McDonnell. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. *Water Resour. Res.*, **38**, 1214 (2002).
[11] K. Beven. Prophecy, reality and uncertainty in distributed hydrological modeling. *Adv. Water Resour.*, **16**, 41 (1993).
[12] J. Gurtz, A. Baltensweiler, H. Lang. Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins. *Hydrol. Processes*, **13**, 2751 (1999).
[13] G.H. Leavesley, S.L. Markstrom, P.J. Restrepo, R.J. Viger. A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling. *Hydrol. Processes*, **16**, 173 (2002).
[14] C. Joerin, K.J. Beven, I. Iorgulescu, A. Musy. Uncertainty in hydrograph separations based on geochemical mixing models. *J. Hydrol.*, **255**, 90 (2002).
[15] S. Uhlenbrook, S. Hoeg. Quantifying uncertainties in tracer-based hydrograph separations: A case study for two-, three-, and five-component hydrograph separations in a mountainous catchment. *Hydrol. Processes*, **17**, 431 (2003).
[16] S.J. Van der Hoven, D.K. Soloman, G.R. Moline. Numerical simulation of unsaturated flow along preferential pathways: Implications for the use of mass balance calculations for isotope storm hydrograph separation. *J. Hydrol.*, **268**, 214 (2002).
[17] V.C. Kennedy, C. Kendall, G.W. Zellweger, T.A. Wyerman, R.J. Avanzino. Determination of the components of stormflow using water chemistry and environmental isotopes, Mattole river basin, California. *J. Hydrol.*, **84**, 107 (1986).
[18] M.G. Sklash, R.N. Farvolden. The role of groundwater in storm runoff. *J. Hydrol.*, **43**, 45 (1979).
[19] M.G. Sklash, R.N. Farvolden. The use of environmental isotopes in the study of high-runoff episodes in streams. In *Isotope Studies of Hydrologic Processes*, E.C. Perry Jr, C.W. Montgomery (Eds.), pp. 65–73, North Illinois University Press, Illinois (1982).
[20] C. Kendall, J. McDonnell, W. Gu. A look inside 'black box' hydrograph separation models: A study at the Hydrohill catchment. *Hydrol. Processes*, **15**, 1877 (2001).
[21] G. Vanenschrick, B. van Wesemael, E. Frot, A. Pulido-Bosch, L. Molina, M. Stiévenard, R. Souchez. Using stable isotope analysis (δD-δ^{18}O) to characterize the regional hydrology of the Sierra de Gador, South East Spain. *J. Hydrol.*, **265**, 43 (2002).
[22] H. Laudon, J. Siebert, S. Köhler, K. Bishop. Hydrological flow paths during snowmelt: Congruence between hydrometric measurements and oxygen 18 in meltwater, soil water, and runoff. *Water Resour. Res.*, **40**, ??? (2004).
[23] A. Güntner, S. Uhlenbrook, J. Siebert, C. Leibundgut. Multi-critical validation of TOPMODEL in a mountainous catchment. *Hydrol. Processes*, **13**, 1603 (1999).
[24] C. Soulsby, P. Rodgers, R. Smart, J. Dawson, S. Dunn. A tracer-based assessment of hydrological pathways at different spatial scales in a mesoscale Scottish catchment. *Hydrol. Processes*, **17**, 759 (2003).
[25] A. Robson, K.J. Beven, C. Neal. Towards identifying sources of subsurface flow: A comparison of components identified by a physically based runoff model and those determined by chemical mixing techniques. *Hydrol. Processes*, **6**, 199 (1992).
[26] C. Wels, R.J. Cornett, B.D. Lazerte. Hydrograph separation: A comparison of geochemical and isotopic tracers. *J. Hydrol.*, **122**, 253 (1991).
[27] International Atomic Energy Agency. *Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle.* Technical reports Series No. 210, IAEA, Vienna (1981).
[28] C. Kendall, J.J. McDonnell (Eds.). *Isotope Tracers in Catchment Hydrology*, Elsevier Science, New York (1998).
[29] K.J. Beven. A discussion of distributed hydrological modelling. In *Distributed Hydrological Modelling*, M.B. Abbott, J.C. Refsgaard (Eds.), Chapter 13A, pp. 255–278, Kluwer Academic Publishers, Dordrecht (1996).
[30] W.R. Rouse, E.M. Blyth, R.W. Crawford, J.R. Gyakum, J.R. Janowicz, B. Kochtubajda, H.G. Leighton, P. Marsh, L. Martz, A. Pietroniro, H. Ritchie, W.M. Schertzer, E.D. Soulis, R.E. Stewart, G.S. Strong, M.K. Woo. Energy and water cycles in a high latitude, north-flowing river system: Summary of results from the Mackenzie GEWEX study, phase 1. *Bull. Amer. Met. Soc.*, **84**, 73 (2003).

[31] R.E. Stewart, H.G. Leighton, P. Marsh, G.W.K. Moore, H. Ritchie, W.R. Rouse, E.D. Soulis, G.S. Strong, R.W. Crawford, B. Kochtubajda. The Mackenzie GEWEX Study: The water and energy cycles of a major North American river basin. *Bull. Am. Met. Soc.*, **70**, 2665 (1998).
[32] L.P.B. Hamlin. Snowmelt hydrologic modelling of northern wetland dominated river basins. MSc thesis, Department of Civil Engineering. University of Waterloo (1996).
[33] J.M. Aylsworth, M.M. Burgess, D.T. Desrochers, A. Duk-Rodkin, T. Robertson, J.A. Traynor. Surficial geology, subsurface materials, and thaw sensitivity of sediments. In *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change*, L.D. Dyke, G.R. Brooks (Eds.), pp. 41–48, Geological Survey of Canada, Ottawa (2000).
[34] T.B. Coplen. New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data. *Geochim. Cosmochim. Acta*, **60**, 3359 (1996).
[35] C. Onclin, T. Carter, K. Best. *Fort Simpson Area Snow Surveys 1996–2002* Publisher (2000).
[36] P.V. Unnikrishna, J.J. McDonnell, C. Kendall. Isotope variations in a Sierra Nevada snowpack and their relation to meltwater. *J. Hydrol.*, **260**, 38 (2002).
[37] H. Laudon, H.F. Hemond, R. Krouse, K.H. Bishop. Oxygen 18 fractionation during snowmelt: Implications for spring flood hydrograph separation. *Water Resour. Res.*, **38**, 1258 (2002).
[38] N. Kouwen. WATFLOOD: A microcomputer based flood forecasting system based on real-time weather radar. *Can. Water Resour. J.*, **13**, 62 (1988).
[39] R. Benoit, N.Yu.W. Kouwen, S. Chamberland, P. Pellerin. Hydrometeorological aspects of the real-time ultra-finescale forecast support during the special observing period of the MAP. *Hydrol. Earth Sys. Sci.*, **7**, 877 (2003).
[40] N. Kouwen, A.S.C.E. Member, E.D. Soulis, A. Pietroniro, J. Donald, R.A. Harrington. Grouped response units for distributed hydrologic modelling. *J. Water Resour. Plan. Manag.*, **119**, 289 (1993).
[41] R. McKillop. Modelling the rainfall-runoff response from a headwater wetland. PhD thesis, Department of Civil Engineering, University of Waterloo (1997).
[42] W.L. Quinton, M. Hayashi, A. Pietroniro. Hydrological characteristics of wetland-dominated northern basins with inter-connected fens. *Hydrol. Processes*, **17**, 3665 (2003).
[43] N. Hopkins, A. Pietroniro, W.L. Quinton, M. Hayashi, M. Hall-Beyer. Evaluating landcover classifications using LANDSAT and Ikonos images: Implications for hydrological modelling in remote regions. *Remote Sensing of Environment* submitted (2005).
[44] Ecoregions Working Group. Ecoclimatic regions of Canada, first approximation. In *Ecoregions Working Group of the Canada Committee on Ecological Land Classification, Sustainable Development Branch, Canadian Wildlife Service. Ecological Land Classification Series 23.* p. 119, Environment Canada, Ottawa (1989).

Appendix A

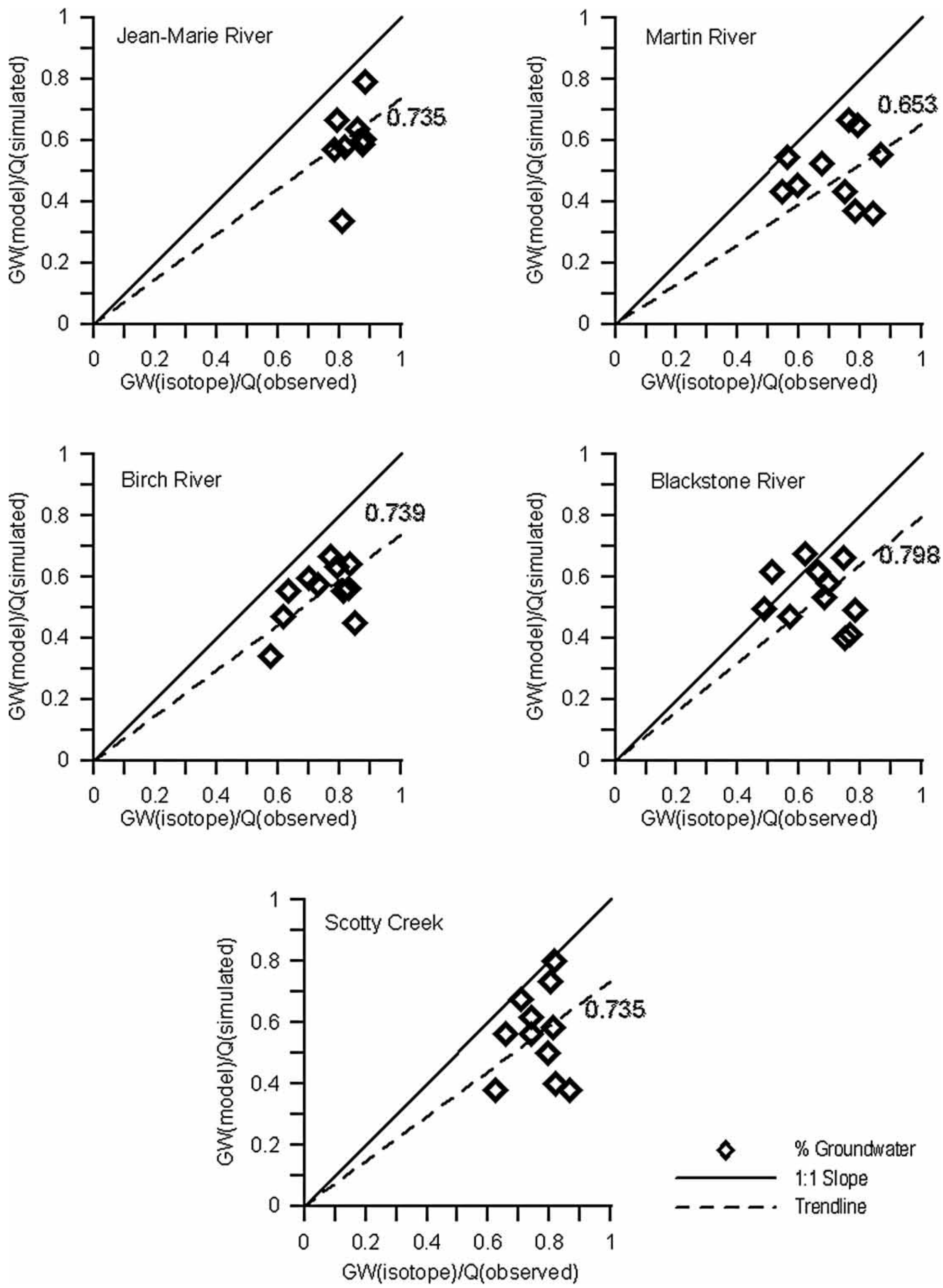

Figure A1.

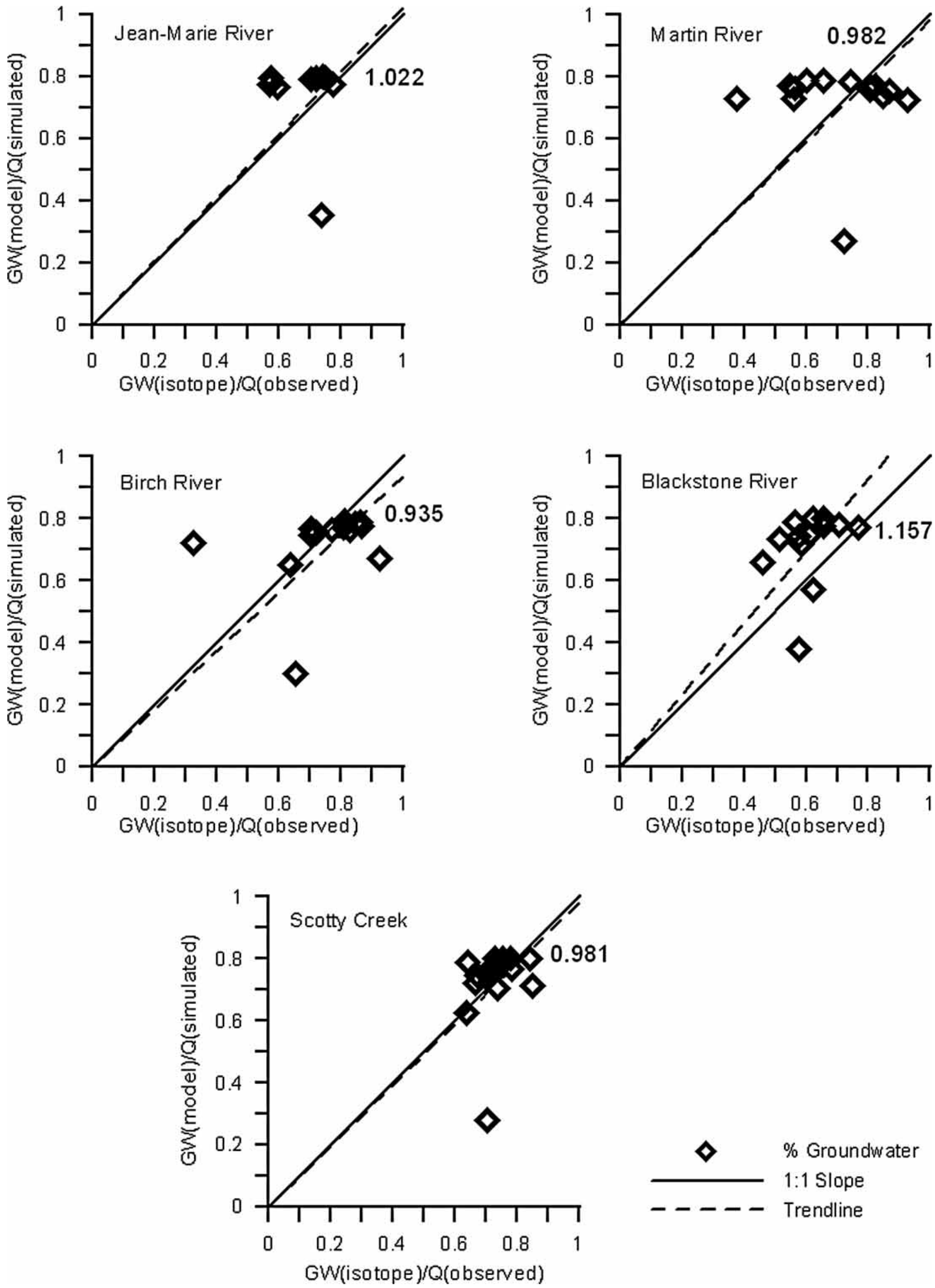
Jean-Marie River
1.022
Martin River
0.982
Birch River
0.935
Blackstone River
1.157
Scotty Creek
0.981
GW(model)/Q(simulated)
GW(isotope)/Q(observed)
0
0.2
0.4
0.6
0.8
1
% Groundwater
1:1 Slope
Trendline

Figure A2.

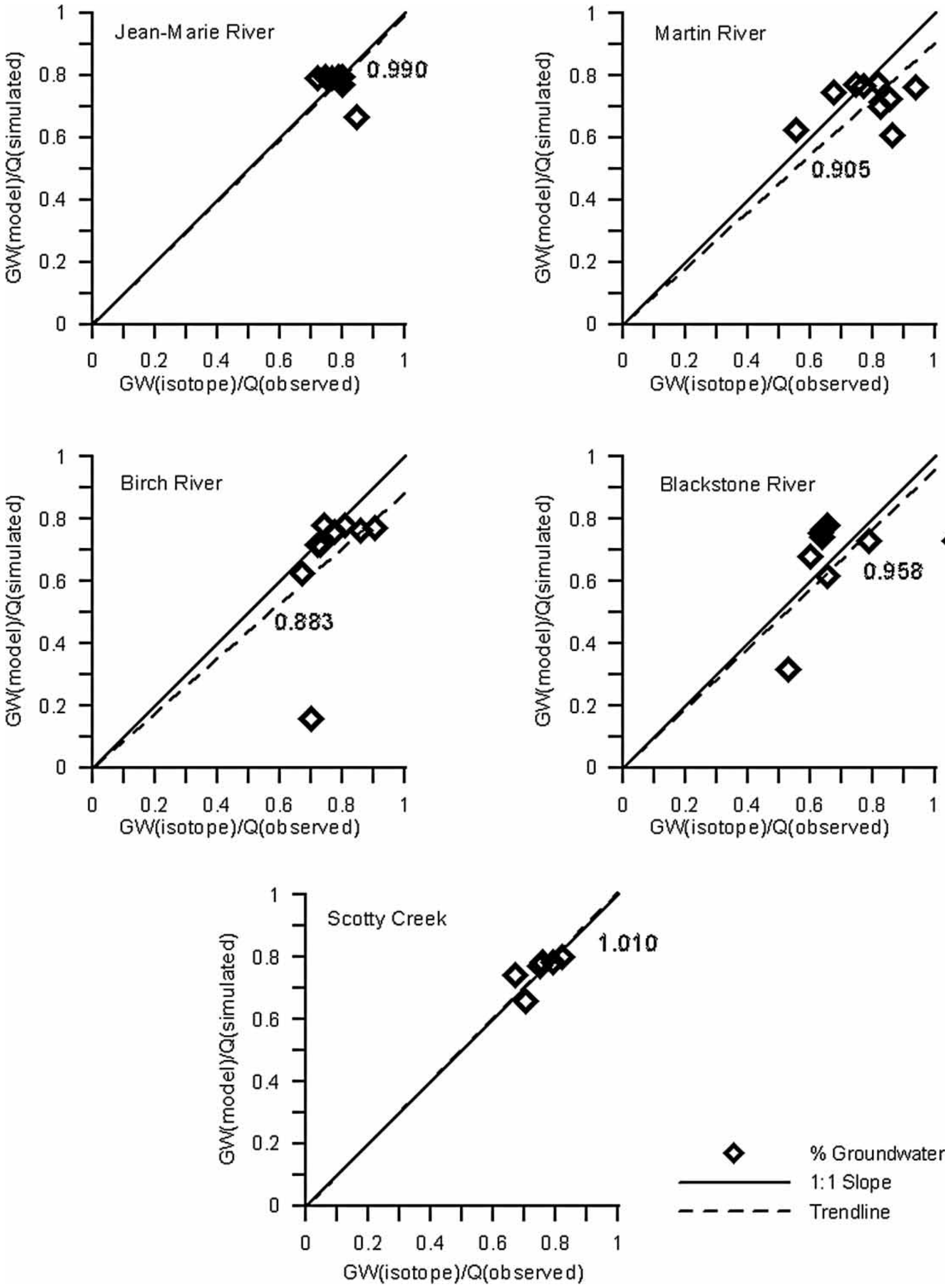
Jean-Marie River
0.990
Martin River
0.905
Birch River
0.883
Blackstone River
0.958
Scotty Creek
1.010
GW(model)/Q(simulated)
GW(isotope)/Q(observed)
0
0.2
0.4
0.6
0.8
1
% Groundwater
1:1 Slope
Trendline

Figure A3.