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Isotope hydrology of the Oldman River basin, southern Alberta, Canada

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Abstract:

The partially semi-arid Oldman River basin (OMRB), located in southern Alberta (Canada), has an area of 28 200 km², is forested in its western headwater part, and is used for agriculture in its eastern part. Hydrometric measurements indicate that flow in the Oldman River has decreased by ~34% between 1913 and 2003, and it is predicted that water withdrawals will increase in the next 20 years. The objective of this study was to determine whether isotope ratio measurements can provide further insight into the water dynamics of the Oldman River and its tributaries. Surface water samples were collected monthly between December 2000 and March 2003. Groundwater samples were taken from 58 wells during one-time sampling trips. Runoff within the OMRB is currently about 70 mm year⁻¹, with a corresponding runoff ratio of 0.18. Seasonal flow characteristics are markedly different upstream and downstream of the Oldman River reservoir. Upstream, sharp increases in flow in late spring and early summer are followed by a rapid decrease to base flow levels. Downstream, a prolonged high flow peak is observed due to the storage effect of the Oldman River reservoir. The seasonal variation in the isotopic composition of surface water from upstream sites is small. This suggests that peak runoff is not predominantly generated by melting snow accumulated during the preceding winter, but mainly by relatively well-mixed young groundwater. A significant increase in the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in the downstream part of the basin was observed. The increase in the isotopic values is partly due to surface water and groundwater influx with progressively higher $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in the eastern part, and partly due to evaporation. Hence, the combination of hydrometric data with isotope measurements yields valuable insights into the water dynamics in the OMRB that may be further refined with more intensive measurement programmes in the future. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS watershed; water dynamics; stable isotopes; $\delta^{18}\text{O}$; $\delta^2\text{H}$; runoff

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INTRODUCTION

In southern Alberta (Canada), water resources are currently under high strain due to both human and natural factors (ABEnv, 2002). Population and economic growth put an increasing demand on water supply, e.g. through intense irrigation to support agriculture within the region. It is expected that non-irrigation water withdrawals will increase by about 40% by 2021 (ABEnv, 2003a). Additionally, climate-change scenarios predict significantly increased temperatures in the Canadian prairies (Sauchyn *et al.*, 2005), and enhanced evaporation and transpiration will likely cause additional alteration of the hydrological cycle in the region. Therefore, a solid understanding of the current hydrological balance in southern Alberta is an essential prerequisite for evaluating potential future changes in water supply.

The Oldman River basin (OMRB; Figure 1) is the largest watershed in southern Alberta. Previous studies investigating water dynamics within the OMRB focused primarily on understanding flow measurement data (e.g. Astatkie *et al.*, 1995; Byrne *et al.*, 1999; Rood *et al.*, 2005) or dealt primarily with groundwater in localized

areas of this watershed (e.g. Nielsen, 1971; Hendry, 1988; Berg and Byrne, 1998). Available oxygen (O) and hydrogen (H) isotope data from surface water within this watershed are limited (Brown *et al.*, 1971). Byrne *et al.* (1999) used a general circulation model, historical upper air circulation data, and historical spring runoff data to predict future changes in runoff within the OMRB. Assuming that most of the runoff in the basin is due to snowmelt, they concluded that there would be a significant increase in spring runoff within this watershed as a consequence of global warming. On the contrary, Rood *et al.* (2005) concluded that there will be a decline in river flow in future decades, based on their finding that river flow declined over the past century. Current knowledge regarding water dynamics in terms of what sources contribute to riverine flow and what processes affect water resources within the entire OMRB is limited, and future predictions are contradictory.

The analysis of stable isotope ratios of hydrogen and oxygen of water samples can provide additional essential information about water dynamics within a given watershed, as illustrated by previous studies. Buhl *et al.* (1991) used $\delta^{18}\text{O}$ values to determine the relative contributions of alpine melt water versus rain and groundwater to the River Rhine. Hydrogen and oxygen isotope ratios

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Figure 1. Map of study area, the OMRB, southern Alberta (Canada) with the main stream, the OMR and some of its tributaries; also shown are the physiographic regions: Rocky Mountains, foothills, and plains. OMR res.: OMR reservoir; evapotranspiration ET and precipitation PPC are based on data from UofA (1969)

can also be used to study evaporation of water bodies and mixing processes between various water sources (e.g. Simpson and Herczeg, 1991; Space *et al.*, 1991; McKenna *et al.*, 1992; Gibson *et al.*, 1993; Kendall and Coplen, 2001; Gibson and Edwards, 2002; Gibson *et al.*, 2005). Only few H and O isotope data have been published for the OMRB (Brown *et al.*, 1971; Hendry, 1988). No comprehensive study has been undertaken of the water dynamics within the OMRB integrating both flow and isotopic data. The objective of this study was to determine whether isotope ratio measurements can provide further insight into the water dynamics within the OMRB.

STUDY AREA

Location

The OMRB is located in southern Alberta, Canada (Figure 1). It covers an area of about 28 200 km², provides water resources for over 200 000 people, and sustains substantial ranching and feedlot operations with currently over 3 million animals. The western part of this watershed is mainly forested, whereas the eastern part is intensively used for agriculture. The OMRB was first settled in the late 1800s. Since the early 1900s, agricultural activities were enhanced by irrigation (AAFRD, 2000),

and irrigation played a key role in the economic development of southern Alberta, as it was perceived as needed to support local agriculture (Johnston, 1997).

The Oldman River (OMR) originates from a small alpine lake on Mt Lyall, a peak on the continental divide in the Canadian Rocky Mountains (ABGov, 1976). It then flows eastward through the foothills of the Canadian Rocky Mountains and the prairies of southwestern Canada, before converging with the Bow River at its mouth to form the South Saskatchewan River (Figure 1), which eventually drains into Hudson Bay. Owing to a highly variable flow pattern and time distribution of runoff from the mountainous part of the watershed, reservoirs were built along the OMR (OMR reservoir built in the late 1980s near the Crow'snest and Castle Rivers, Figure 1) and some of its tributaries (e.g. St Mary and Little Bow rivers, Figure 1) to regulate the flow and to store water for irrigation necessary for sustaining agricultural production under the predominantly semi-arid climate in the eastern part of the OMRB.

Climate

Based on a 30-year record (1971–2000), the mean annual precipitation varies from more than 580 mm in the western mountainous part of the watershed to around 380 mm in the eastern part of the basin, and the mean annual temperature varies between +3 °C and +6 °C respectively (EnvCan, 2004). The mean monthly

temperatures vary between -5°C in the winter and $+13^{\circ}\text{C}$ in the summer in the western region, and between -4°C in the winter and $+16^{\circ}\text{C}$ in the summer in the eastern region. The mean monthly precipitation varies between 40 mm in the winter and 52 mm in the summer in the western region, and between 18 mm in the winter and 44 mm in the summer in the eastern region. During the duration of this research project, dry and wet years occurred relative to the average 30-year precipitation values of 1971–2000. Whereas 2000 was a dry year, 2002 was a wet year. Within the OMRB, mean annual potential evapotranspiration ranges from about 350 mm in its western part to about 600 mm in its eastern part (UofA, 1969). Hence, throughout most of the basin, potential evapotranspiration exceeds precipitation, except for the western headwater area (Figure 1). Hence, most of the basin is characterized by a semi-arid climate. This leads to moisture deficiencies, and makes irrigation essential to ensure agricultural production. Today, irrigation districts in the eastern part of the basin cover about 11% of the entire watershed (OMRBWQI, 2002). The irrigation season starts in May and ends in October.

Water usage

In Alberta, surface water currently provides 98% of the water consumed, with the remainder being derived from groundwater (ABEnv, 2002). Within the OMRB, 88% of the licensed water is allocated to agriculture, with the majority (87%) used for irrigation (ABEnv, 2003b). Water management and commercial use each account for 4%, and municipal use for 3% of the allocations. Habitat enhancement and recreation each account for less than 0.5% of the total water allocations within the OMRB (ABEnv, 2003b).

The allocation volume, especially in drought years, may exceed the available temporal unevenly distributed flow, which is frequently mitigated through storage (e.g. reservoirs). Between 1976 and 2003, the Lethbridge Northern Irrigation District (LNID) diverted on average $2.1 \times 10^8 \text{ m}^3 \text{ year}^{-1}$ from the OMR (AAFRD, 2004a). The LNID diverts the water about 50 km downstream of the OMR reservoir (Figure 1). Note that water is not only diverted from the OMR, but also from some of its tributaries (e.g. Belly River). Based on data from Alberta Agriculture Food and Rural Development (AAFRD, 2004a), an average annual volume of $9.37 \times 10^8 \text{ m}^3$ was diverted between 1976 and 2003 within the OMRB. This represents about 42% of the average annual outflow of $2.22 \times 10^9 \text{ m}^3$ (based on a 25-year record) from the OMR at its mouth (WSC, 2004). From the water allocated to non-irrigation use, about 23% was returned in 1996 to the OMRB, and it is projected that this number will decrease to 17% in 2046 (ABEnv, 2003a). Regarding water diverted for irrigation usage, return flow accounted on average for up to 28% of the total gross diversion during 1997 to 2000 (AIPA, 2002). Additionally, evaporation losses from canals and

reservoirs, excluding headwater works, are estimated to about 0.5% ($2 \times 10^6 \text{ m}^3 \text{ year}^{-1}$) of the licensed volume for the LNID, which diverts water from the main stem of the OMR, and to about 3.8% ($65.5 \times 10^6 \text{ m}^3 \text{ year}^{-1}$) of the licensed volume for all irrigation districts within the OMRB (AIPA, 2002). About 40% of the diverted water becomes 'virtual water', which is water needed to produce a certain crop or product, and/or may be partly stored as groundwater.

SAMPLING SITES

Surface water samples for H and O isotope ratio measurements were collected from 25 sites throughout the OMRB in collaboration with Alberta Environment, and Alberta Agriculture, Food and Rural Development. The sampling sites included 12 OMR sites and 13 tributaries (Figure 2, Table I). Note that their location (kilometres) along the OMR is given relative to the outlet of the OMR dam. Water (60 ml) was collected from the fast-flowing part of the river or tributaries and returned to the laboratory in thoroughly closed HDPE bottles. Sampling was conducted once per month between December 2000 and March 2003 (Table I). Note that not all sites were sampled continuously throughout the entire sampling period.

Groundwater was collected once from 58 different wells located in the northern and eastern parts of the OMRB (Figure 2, Table II). The wells in the eastern part were located near Lethbridge in the agricultural fields belonging to the Agriculture and Agri-Food Canada Lethbridge research station. They were sampled in July and August 2003, and will be referred to as the eastern site. The wells in the northern part of the OMRB are located adjacent or close to the Little Bow River. They were sampled in November 2001, and will be referred to as the northern site.

METHODS

Flow measurements were provided by Alberta Environment, by Alberta Agriculture, Food, and Rural Development, and by the LNID, or were downloaded from the Water Survey of Canada webpage (WSC, 2004). Not all sampling stations along the main stem of the OMR had gauging stations. The flow at those stations was calculated based on the flow at the closest upstream gauging station plus flows of tributaries, assuming no loss of water via evaporation or seepage into groundwater.

O and H isotope ratios were determined for all water samples. The $^{18}\text{O}/^{16}\text{O}$ ratios were determined using the $\text{CO}_2\text{--H}_2\text{O}$ equilibration technique (Epstein and Mayeda, 1953). $^2\text{H}/^1\text{H}$ ratios were determined using the zinc reduction technique (Friedman, 1953; Coleman *et al.*, 1982) or the chromium reduction technique (Gehre *et al.*, 1996; Donnelly *et al.*, 2001; Nelson and Dettman, 2001). The conventional δ notation is used to express the stable

Table I. Sampling sites for surface water: OMR and tributary sites sampled from December 2000 to April 2003 (indicated by ×); also shown for each site is the distance relative to the outlet of the OMR reservoir. See Figure 2 for site locations

Site	Abbreviation	Site description	Distance (km) relative to OMR reservoir	Dec 00–Mar 01	Apr 01–Mar 02	Apr 02–Mar 03
1	OMROC	OMR near Olin Creek R	−32.93		×	×
2	CRR	Crowsnest River upstream of Connelly Creek	−13.82		×	×
3	CAR	Castle River at Castle River Recreation Area	−9.34	×	×	×
4	OMR100m	OMR 100 m d/s of dam bottom release L	0.10			×
5	OMRB	OMR near Brocket L	6.41	×	×	×
6	PC	Pincher Creek at Hwy 3 near the mouth	12.15			×
7	BC	Beaver Creek at Hwy 785 west of Peigan Reserve	28.97	×	×	×
8	OMRFM	OMR at Fort MacLeod R	65.59			×
9	WC	Willow Creek at Hwy 811	77.84			×
10	OMRM	OMR near Monarch R	115.02			×
11	BR	Belly River upstream of confluence with OMR	124.19			×
12	OMRBR	OMR downstream of Belly River L	137.42			×
13	STMR	St Mary River upstream of confluence with OMR	156.47			×
14	OMRPP	OMR at Popson Park L	159.80			×
15	SMC	SIX MILE COULEE Spillway	164.81	×	×	×
16	OMRH3	OMR at Hwy 3 Bridge R	171.32	×	×	×
17	OMRDC	OMR southwest of Diamond City R	182.11		×	×
18	PD	Piyami Drain	196.74	×	×	×
19	HD	Haney Drain	213.35	×	×	×
20	OMRH845	OMR d/s of Picture Butte at Hwy 845 L	213.72			×
21	BD	Battersea Drain	215.62	×	×	×
22	LBR	Little Bow River	227.67	×	×	×
23	OMRH864	OMR above Taber at Hwy 864 L	257.24			×
24	OMRH36	OMR at Hwy 36 Bridge L	281.46	×	×	×
25	EC	Expanse Coulee	281.56	×	×	×

Figure 2. Map of surface water and groundwater sampling sites within the OMRB. See Tables I and II for sampling site descriptions

Figure 3. Flow versus time for the OMR site at highway #3 (site #16, kilometre 171) from 1913 to 2003. Based on data from WSC (2004)

Table II. Sampling sites for groundwater. See Figure 2 for site locations

Site	Site description	No. of wells
Northern	Wells adjacent or close to the Little Bow River	22
Eastern	Wells from agricultural fields of AAFC ^a	36

^a AAFC: Agriculture & Agri-Food Canada.

isotope compositions of H and O in the water samples:

$$\delta_{\text{sample}} (\text{‰}) = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000$$

where R_{sample} and R_{standard} denote the $^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$ ratios of the sample and reference materials respectively. The standard for both H and O isotope measurements is the Vienna standard mean ocean water (V-SMOW) established and distributed by the International Atomic Energy Agency (IAEA) in Vienna, Austria. Standardization of the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ measurements was achieved using the IAEA reference materials V-SMOW, Greenland ice sheet precipitation, and standard light Antarctic precipitation (SLAP) for calibration, following the guideline of Coplen (1996), so that the $\delta^2\text{H}$ value of SLAP is -428‰ and its $\delta^{18}\text{O}$ value is -55.5‰ . The uncertainty of $\delta^2\text{H}$ measurements was better than $\pm 2\text{‰}$, whereas that of $\delta^{18}\text{O}$ measurements was better than $\pm 0.2\text{‰}$.

RESULTS AND DISCUSSION

Based on flow measurement data from 1983–2003 (WSC, 2004) for the OMR station near its mouth, runoff within the OMRB is currently about 70 mm year⁻¹. Based on an average precipitation of 400 mm year⁻¹ for the OMRB, the corresponding runoff ratio for the OMRB is 0.18, which is lower than the average

runoff ratio for North America of about 0.38 (Berner, 1987). Furthermore, based on flow measurement data (WSC, 2004) from 1913 to 2003 for the OMR at highway #3 (site #16, 171 km downstream of the outlet of OMR reservoir), there is a trend of decreasing flow with time within the OMRB (Figure 3) from an average of about $3.5 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ (1913–1923) to about $2.3 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ (1993–2003). In all likelihood, the decrease in flow between the early and late 1900s is partly related to the increased demand on water resources by irrigation. This is based on the observations that there is a significant increase in the irrigation area with time and that total precipitation within the watershed neither increased nor decreased with time (Figure 4). Hence, it appears that water demand increased over time but water supply remained fairly constant.

In the following, we will discuss flow and isotope data for the low-flow year April 2001 to March 2002, and the high-flow year April 2002 to March 2003. The latter was characterized by a flood event that occurred in June 2002 due to a high intensity rainstorm.

Runoff

Seasonal flow distributions are markedly different upstream and downstream of the OMR reservoir (Figure 5). Upstream of the OMR reservoir, runoff Q at the OMR site near Olin Creek (site #1, kilometre -33) ranged from 0.800 to 54.300 $\text{m}^3 \text{ s}^{-1}$, with a mean of 5.426 $\text{m}^3 \text{ s}^{-1}$ between April 2001 and March 2002 (Table III), and Q ranged from 1.600 to 180.000 $\text{m}^3 \text{ s}^{-1}$, with a mean of 16.799 $\text{m}^3 \text{ s}^{-1}$ between April 2002 and March 2003 (Table III). The highest flow was observed during late spring, with the maximum occurring in June (Figure 5a and b). During summer, fall and winter, flow was much lower and never exceeded 8 $\text{m}^3 \text{ s}^{-1}$. For the tributaries Crowsnest River (site #2, kilometre -14) and Castle River (site #3, kilometre -9), flow ranged from 0.863 to 15.067 $\text{m}^3 \text{ s}^{-1}$ (mean: 2.956 $\text{m}^3 \text{ s}^{-1}$) and from

Figure 4. (a) Evolution of irrigation area versus time within 13 irrigation districts of Alberta (modified after AIPA (2002)); (b) total precipitation versus time for the western and eastern regions of the OMRB (data from EnvCan (2004))

1.400 to 89.800 $\text{m}^3 \text{s}^{-1}$ (mean: 8.992 $\text{m}^3 \text{s}^{-1}$) respectively between April 2001 and March 2002 (Table III), and flow ranged from 1.133 to 66.800 $\text{m}^3 \text{s}^{-1}$ (mean: 8.611 $\text{m}^3 \text{s}^{-1}$) and 1.500 to 225.000 $\text{m}^3 \text{s}^{-1}$ (mean: 21.868 $\text{m}^3 \text{s}^{-1}$) respectively between April 2002 and March 2003 (Table III). Similar to the OMR site near Olin Creek, the highest runoff was observed in late spring, with the maximum occurring in June (Figure 5a and b). During the rest of the year, flow was markedly lower. The high ratios of $Q_{\max}/Q_{\min}$ of more than 50 for the rivers above the OMR reservoir are characteristic for snowmelt-dominated mountainous river systems with sharp increases in flow in late spring and early summer due to snowmelt and occasionally heavy rains followed by a rapid decrease to base flow levels (Figure 5a and b).

At 6 km downstream of the OMR reservoir, runoff at the OMR site near Brocket (site #5, kilometre 6) varied between 6.760 and 65.100 $\text{m}^3 \text{s}^{-1}$, with a mean of 23.969 $\text{m}^3 \text{s}^{-1}$ between April 2001 and March 2002 (Table III), and ranged from 6.300 to 553.000 $\text{m}^3 \text{s}^{-1}$, with a mean of 44.984 $\text{m}^3 \text{s}^{-1}$ between April 2002 and March 2003 (Table III). The highest flow was observed during late spring and summer, with the maximum occurring in July, followed by a slow decrease of the flow throughout the summer months. During fall and winter, flow never exceeded 15 $\text{m}^3 \text{s}^{-1}$ (Figure 5c and d). The storage effect of the OMR reservoir results in a $Q_{\max}/Q_{\min}$ ratio of ~ 10 and in a prolonged high flow peak which extends far into the summer months. The OMR reservoir, with a capacity of $4.9 \times 10^8 \text{ m}^3$

Table III. Summary statistics for flow ($\text{m}^3 \text{s}^{-1}$) data from April 2001 to March 2002 and from April 2002 to March 2003

Site	N	Mean	SD	Min.	Max.	Range
<i>April 2001 to March 2002</i>						
1	365	5.426	7.581	0.800	54.300	53.500
2	365	2.956	3.120	0.863	15.067	14.204
3	365	8.992	14.541	1.400	89.800	88.400
5	365	23.969	18.461	6.760	65.100	58.340
7	128	0.105	0.127	0.001	0.714	0.713
15	168	0.187	0.151	0.000	0.819	0.818
16	365	19.804	7.943	7.000	75.000	68.000
17 ^a	12	21.583	7.573	10.000	37.000	27.000
18	181	0.679	0.293	0.001	1.540	1.539
19 ^b	0					
21	174	0.585	0.245	0.001	1.159	1.158
22	190	1.241	0.449	0.418	2.460	2.042
24	12	22.611	7.698	10.651	39.064	28.413
25	190	0.752	0.368	0.030	1.630	1.600
<i>April 2002 to March 2003</i>						
1	365	16.799	31.459	1.600	180.000	178.400
2	365	8.611	13.570	1.133	66.800	65.667
3	365	21.868	42.364	1.500	225.000	223.500
4 ^a	12	59.000	102.981	6.000	333.000	327.000
5	365	44.984	85.579	6.300	553.000	546.700
6	245	3.210	6.604	0.065	62.800	62.735
7	241	1.259	3.460	0.001	33.100	33.099
8	128	76.015	125.323	14.628	612.670	598.042
9	245	7.126	17.143	0.390	142.000	141.610
10 ^a	2			18.961	32.550	
11	135	48.342	78.072	0.681	332.420	331.739
12 ^a	2			35.068	39.803	
13	365	17.193	35.012	2.300	196.000	193.700
14 ^a	2			45.513	54.068	
15	171	0.411	0.849	0.001	7.113	7.112
16	365	103.090	211.497	11.800	1590.000	1578.200
17 ^a	12	207.500	461.776	15.000	1591.000	1576.000
18	185	0.728	1.200	0.008	10.300	10.292
19 ^b	11	0.079	0.223	0.001	0.750	0.749
20 ^a	12	208.000	462.600	15.000	1594.000	1579.000
21	174	0.652	0.372	0.001	2.265	2.264
22	190	2.975	1.957	0.550	11.000	10.450
23 ^a	12	210.833	466.066	16.000	1608.000	1592.000
24	12	210.817	465.989	15.916	1607.860	1591.950
25	190	0.704	0.410	0.020	2.380	2.360

^a No gauging station, calculated.

^b Spot measurement.

(AAFRD, 2004b), has an annual average inflow of $1.1 \times 10^9 \text{ m}^3$ from the OMR (site #1, kilometre -33), Crowsnest River (site #2, kilometre -14), and Castle River (site #3, kilometre -9). Assuming that groundwater recharge to the reservoir is negligible, the mean residence time of water within the OMR reservoir is around 0.45 years. Hence, this is the upper estimate for the residence time t . If groundwater contributes to a certain extent, t will be lower than 0.45 years.

Three other OMR sites located between kilometre 171 and kilometre 281 below the OMR reservoir had flows ranging from 7.000 to 75.000 $\text{m}^3 \text{s}^{-1}$ between April 2001 and March 2002, and from 11.800 to 1607.860 $\text{m}^3 \text{s}^{-1}$ between April 2002 and March 2003 (Table III). Assuming no major losses to groundwater, the flows at these sites located downstream of kilometre 50 should be

Figure 5. Flow versus time for OMR and tributary sites located above the OMR reservoir for (a) April 2001 to March 2002 and (b) April 2002 to March 2003, for some OMR sites downstream of the reservoir for (c) April 2001 to March 2002 and (d) April 2002 to March 2003, and some tributaries located downstream of the reservoir for (e) April 2001 to March 2002 and (f) April 2002 to March 2003. Note that, for each site, daily flow measurements are indicated by a line (if available), and flow at sampling date is indicated by a symbol. See Tables I and II for site descriptions

higher than at kilometre 6 due in part to the influx of water from tributaries such as the Belly River. During the irrigation season between May and September 2001, however, flows at OMR sites located downstream of kilometre 50 were significantly reduced compared with the flow at the OMR site at Brocket, kilometre 6 (Figure 5c). For instance, around 10 July 2001, flow at kilometre 171 was about $24 \text{ m}^3 \text{ s}^{-1}$ compared with about $62 \text{ m}^3 \text{ s}^{-1}$ at kilometre 6. Hence, flow decreased by about 60%. The observed decrease is linked to the diversion of OMR water at kilometre 50 for irrigation purposes

by the LNID. In 2001, the LNID diverted $3.4 \times 10^8 \text{ m}^3$ (AAFRD, 2004a) from the OMR to its irrigation district located north and east of Lethbridge, which corresponds to about 45% of the mean annual flow in 2001 upstream of kilometre 50.

During the non-irrigation season between October and March, the flows at the three OMR stations between kilometres 171 and 281 are significantly higher than that at Brocket (kilometre 6) (Figure 5c). This is partially caused by influx from tributaries, such as the Belly and St Mary Rivers. The St Mary River had an average flow

Figure 6. $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values versus time for OMR and tributary sites located above the OMR reservoir for (a) April 2001 to March 2002 and (b) April 2002 to March 2003, for some OMR sites downstream of the reservoir for (c) April 2001 to March 2002 and (d) April 2002 to March 2003, and some tributaries located downstream of the reservoir for (e) April 2001 to March 2002 and (f) April 2002 to March 2003. See Tables I and II for site descriptions

of $17 \text{ m}^3 \text{ s}^{-1}$ and the Belly River of about $48 \text{ m}^3 \text{ s}^{-1}$ between April 2002 and March 2003 (Table III). In October 2002, tributary influx accounted for 66% of the increase in flow observed between the OMR site at Fort Macleod (site #8, kilometre 66) and the OMR site at highway #3 (site #16, kilometre 171). The flow at Fort Macleod in addition to the tributary influx did not account entirely for the flow measured at highway #3 (Rock, 2005). Hence, 33% of the increase in flow, or $2.626 \text{ m}^3 \text{ s}^{-1}$, could not be explained by conservative

mixing of OMR and tributary water. Therefore, we speculate that the flow component of $2.626 \text{ m}^3 \text{ s}^{-1}$ corresponding to about 5% of the flow measured at kilometre 171 is derived from groundwater discharge to the OMR between kilometres 66 and 171 in the non-irrigation season.

Runoff within the tributaries located downstream of kilometre 171 (site #16) was much lower than that compared with the OMR and upstream tributaries (Castle and Crowsnest Rivers). The mean flow of most tributaries

Table IV. Summary statistics for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for surface water samples (for April 2001 to March 2002 and for April 2002 to March 2003) and for groundwater samples. See Figure 2 for site locations and Tables I and II for site descriptions

Site	N	Variable	Mean (‰)	SD (‰)	Min. (‰)	Max. (‰)	Range (‰)
<i>Surface water, April 2001–March 2002</i>							
1	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.6	0.7	−20.2	−17.8	2.4
1	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−145	3	−151	−139	12
2	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.7	0.4	−18.3	−17.1	1.2
2	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−137	3	−143	−133	10
3	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.9	0.7	−19.1	−16.9	2.2
3	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−138	3	−143	−135	8
5	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.4	0.3	−17.8	−16.8	1.0
5	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−137	2	−141	−132	9
7	4	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.3	2.3	−20.0	−14.5	5.5
7	4	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−140	13	−157	−130	27
15	8	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−16.1	1.2	−18.5	−14.7	3.8
15	8	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−130	8	−148	−122	26
16	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−16.7	0.6	−17.3	−15.4	1.9
16	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−133	3	−138	−129	9
17	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−16.5	0.4	−17.1	−16.0	1.1
17	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−132	4	−136	−123	13
18	7	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−16.2	0.7	−17.7	−15.4	2.3
18	7	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−132	6	−144	−126	18
19	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−14.8	0.4	−15.5	−14.0	1.5
19	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−125	4	−131	−116	15
21	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−15.4	0.6	−16.8	−14.7	2.1
21	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−128	5	−138	−119	19
22	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−15.7	0.8	−16.9	−14.6	2.3
22	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−132	5	−139	−123	16
24	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−16.1	0.6	−17.1	−15.4	1.7
24	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−130	4	−137	−123	14
25	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−12.8	2.1	−15.6	−9.1	6.5
25	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−119	9	−134	−105	29
O	60	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.1	1.0	−20.2	−15.4	4.8
O	60	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−135	6	−151	−123	28
T	91	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−15.9	1.9	−20.0	−9.1	10.9
T	91	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−131	9	−157	−105	52
<i>Surface water, April 2002–March 2003</i>							
1	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.8	0.2	−19.0	−18.3	0.7
1	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−142	2	−146	−138	8
2	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.0	0.2	−18.3	−17.5	0.8
2	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−135	2	−137	−132	5
3	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.3	0.2	−18.7	−17.9	0.8
3	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−137	3	−141	−132	9
4	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.3	0.4	−19.1	−17.8	1.3
4	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−138	2	−141	−134	7
5	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.1	0.3	−18.7	−17.5	1.2
5	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−136	3	−141	−132	9
6	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.3	0.8	−19.5	−17.5	2.0
6	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−140	3	−144	−137	7
7	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.5	0.5	−19.1	−17.4	1.7
7	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−142	5	−149	−134	15
8	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.4	0.5	−19.1	−18.0	1.1
8	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−139	3	−141	−134	7
9	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.2	0.6	−19.2	−17.6	1.6
9	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−142	5	−148	−135	13
10	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−18.2	0.4	−18.8	−17.8	1.0
10	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−139	6	−145	−129	16
11	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.6	0.4	−18.2	−17.3	0.9
11	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−137	4	−141	−133	8
12	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.9	0.5	−18.5	−17.3	1.2
12	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−138	3	−143	−134	9
13	5	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.0	0.6	−18.1	−16.7	1.4
13	5	$\delta^2\text{H}_{\text{H}_2\text{O}}$	−130	2	−132	−128	4
14	4	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	−17.7	0.4	−18.1	−17.3	0.8

(continued overleaf)

Table IV. (Continued)

Site	N	Variable	Mean (‰)	SD (‰)	Min. (‰)	Max. (‰)	Range (‰)
14	4	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-138	4	-143	-134	9
15	11	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-16.9	1.8	-20.0	-14.8	5.2
15	11	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-133	12	-157	-122	35
16	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.5	0.6	-18.0	-15.7	2.3
16	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-134	3	-141	-129	12
17	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.4	0.5	-17.9	-16.3	1.6
17	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-133	4	-142	-128	14
18	7	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-16.6	0.7	-18.0	-15.9	2.1
18	7	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-132	6	-142	-126	16
19	11	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-15.2	0.7	-16.3	-14.3	2.0
19	11	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-126	5	-134	-119	15
20	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.5	0.6	-18.7	-16.3	2.4
20	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-135	4	-144	-129	15
21	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-15.6	0.7	-16.8	-14.5	2.3
21	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-128	5	-135	-119	16
22	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-16.5	0.6	-18.1	-15.8	2.3
22	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-133	4	-140	-127	13
23	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.5	0.5	-18.5	-16.7	1.8
23	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-135	3	-142	-131	11
24	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.5	0.6	-18.5	-16.3	2.2
24	12	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-134	3	-140	-129	11
25	12	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-12.7	1.1	-14.5	-11.3	3.2
25	11	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-116	7	-131	-107	24
O	115	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-17.8	0.7	-19.1	-15.7	3.4
O	115	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-136	4	-146	-128	18
T	132	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-16.8	1.8	-20.0	-11.3	8.7
T	131	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-132	9	-157	-107	50
<i>Groundwater samples</i>							
Eastern	36	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-16.2	0.5	-17.2	-15.1	2.1
Eastern	36	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-128	4	-139	-122	17
Northern	22	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$	-18.7	0.7	-19.6	-16.3	3.3
Northern	22	$\delta^2\text{H}_{\text{H}_2\text{O}}$	-148	4	-155	-133	22

below kilometre 171 was less than $1 \text{ m}^3 \text{ s}^{-1}$ (Table III). The highest flow within the tributaries occurred throughout the irrigation season from May to October (Figure 5e and f). Note the distinct shape in the hydrograph compared with the upstream tributaries. High flows occur over a longer period of time within the eastern compared with the western tributaries.

Isotope composition of the water

Seasonal variation. H and O isotope ratios of water may provide further insights into the sources of river water and processes in the hydrological cycle, such as mixing and evaporation. Summary statistics for the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of water from the OMR and tributary stations and groundwater are listed in Table IV. Figure 6 shows the $\delta^{18}\text{O}$ values of water from some of the OMR and tributary stations versus time. Also shown are the 10-year monthly mean $\delta^{18}\text{O}$ values of precipitation in southern Alberta based on measurements conducted at Calgary (Peng *et al.*, 2004). Precipitation in southern Alberta is characterized by a strong seasonality, with $\delta^{18}\text{O}$ values between -24 and -27‰ from November to March and $\delta^{18}\text{O}$ values between -18 and -15‰ from May through to October.

Despite the large seasonal variation of more than 10‰ in the amount-weighted average monthly $\delta^{18}\text{O}$ values of

precipitation, the seasonal variation of the $\delta^{18}\text{O}$ values in the OMR and its tributaries above the Oldman dam was less than 2.5‰ (Figure 6a and b). Even during peak runoff in June (Figure 5a and b), there was hardly any excursion towards more negative $\delta^{18}\text{O}$ values indicative of snowmelt-derived winter precipitation. This indicates that the peak runoff is not predominantly generated by melting snow accumulated during the preceding winter, but to a significant proportion of well-mixed groundwater that must have infiltrated prior to the preceding winter, a phenomenon known as the 'old water paradox'. Kirchner (2003: 871) defined the old water paradox as 'streamflow responds promptly to rainfall inputs, but fluctuations in passive tracers (such as water isotopes) are strongly damped'. The very modest seasonal variations in the $\delta^{18}\text{O}$ values of river water suggest that young groundwater is a major contributor to the flow in the OMR and its tributaries above the Oldman reservoir, even during snowmelt periods.

Below the OMR reservoir, the seasonal variation observed in the $\delta^{18}\text{O}$ values measured for the OMR sampling sites never exceeded 2.3‰ , and was less than 1.5‰ for most sampling sites in over 50% of the cases (Table IV, Figure 6c and d). The OMR site at Brocket was characterized by seasonal variations in $\delta^{18}\text{O}$ values of less than 1.3‰ partially due to a homogenization of the

isotope signal associated with the residence time of about 0.45 years of water in the OMR reservoir. The OMR sites at kilometre 171 and kilometre 281 were characterized by seasonal variations in $\delta^{18}\text{O}$ values between 1.4 and 1.9‰. For the tributaries, the seasonal variation in the $\delta^{18}\text{O}$ values was <2.5‰ in 80% of the cases (Table IV, Figure 6e and f).

Although the seasonal variation in $\delta^{18}\text{O}$ values was small for all sites investigated, there was a significant increase in the mean $\delta^{18}\text{O}$ values from around -18.5‰ in the western (upstream) part of the watershed to around -14.5‰ in the eastern (downstream) part of the basin (Table V, Figure 7).

Spatial variation. Arithmetic and flow weighted average annual $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for the individual sampling stations for April 2001 to March 2002 and April 2002 to March 2003 are given in Table V. The flow weighted average values were obtained using the following equation, as illustrated for $\delta^{18}\text{O}$:

$$\delta^{18}\text{O}_i = \frac{\delta^{18}\text{O}_{y,i}Q_{y,i} + \delta^{18}\text{O}_{y+1,i}Q_{y+1,i} + \dots}{Q_{y,i} + Q_{y+1,i} + \dots}$$

where i is the sampling site and y and $y + 1, \dots$ are the sampling months (April, May, ...).

For the period April 2001 to March 2002, arithmetic and flow-weighted average $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values were similar at each sampling site (Table V). For the OMR sites, the arithmetic average annual $\delta^{18}\text{O}$ values ranged from -18.6‰ at kilometre -33 to -16.1‰ at kilometre 281, and the flow-weighted average annual $\delta^{18}\text{O}$ values ranged from -18.8‰ at kilometre -33 to -16.0‰

Figure 7. Arithmetic and flow-weighted annual average $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values versus downstream distance for (a) the OMR sites and (b) tributary sites. See Tables I and II for site descriptions

at kilometre 281. The mean $\delta^{18}\text{O}$ values gradually increased with downstream distance along the OMR

Table V. Flow-weighted and arithmetic average annual $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for April 2001 to March 2002 and April 2002 to March 2003. See Figure 2 for site locations and Table I for site descriptions

Site	N	April 2001–March 2002				Site	N	April 2002–March 2003			
		Flow-weighted average		Arithmetic average				Flow-weighted average		Arithmetic average	
		$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	$\delta^2\text{H}_{\text{H}_2\text{O}}$ (‰)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	$\delta^2\text{H}_{\text{H}_2\text{O}}$ (‰)			$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	$\delta^2\text{H}_{\text{H}_2\text{O}}$ (‰)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	$\delta^2\text{H}_{\text{H}_2\text{O}}$ (‰)
<i>OMR sites</i>											
1	12	−18.8	−143	−18.6	−145	1	12	−18.8	−141	−18.8	−142
5	12	−17.4	−137	−17.4	−137	4	12	−18.3	−138	−18.2	−138
16	12	−16.8	−132	−16.7	−133	5	12	−18.2	−139	−18.1	−137
17	12	−16.5	−132	−16.5	−132	16	12	−17.7	−139	−17.4	−135
24	12	−16.0	−130	−16.1	−130	17	12	−17.2	−139	−17.4	−133
						20	12	−18.3	−139	−17.5	−134
						23	12	−18.2	−138	−17.5	−134
						24	12	−18.2	−137	−17.5	−134
<i>Tributary sites</i>											
2	12	−17.9	−137	−17.7	−138	2	12	−18.1	−135	−18	−135
3	12	−18.7	−138	−17.9	−138	3	12	−18.5	−139	−18.3	−137
7	4	−18.3	−143	−17.3	−140	7	12	−18.4	−145	−18.5	−142
15	8	−16.1	−128	−16.1	−130	15	11	−17.7	−133	−16.9	−133
18	7	−16.0	−130	−16.2	−132	18	7	−16.0	−129	−16.6	−132
21	12	−15.2	−126	−15.4	−128	19	11	−15.6	−133	−15.2	−126
22	12	−15.6	−131	−15.7	−132	21	12	−15.7	−127	−15.6	−128
25	12	−14.6	−125	−12.8	−119	22	12	−16.4	−130	−16.5	−133
						25	12	−13.3	−115	−12.8	−114

(Figure 7a). For the tributaries, arithmetic average annual $\delta^{18}\text{O}$ values ranged from -17.9 to -12.8‰ , and flow-weighted average annual $\delta^{18}\text{O}$ values ranged from -18.7 to -14.6‰ . As for the OMR sites, the lowest values were observed for the western tributaries (e.g. Crowsnest River, site #2, kilometre -14) and the highest values for the eastern tributaries (e.g. Expanse Coulee, site #25, kilometre 282) (Figure 7b).

For the period between April 2002 and March 2003, the arithmetic average $\delta^{18}\text{O}$ values also indicated a trend of increasing values from -18.8 to -17.4‰ with downstream distance (Figure 7), although the increase was, with 1.4‰ , only half of that observed in the period April 2001 to March 2002 (2.8‰). The flow-weighted average $\delta^{18}\text{O}$ values, however, did not indicate a significant increase with downstream distance (Figure 7). This is because of the June 2002 flood, which accounted for between 50 and 70% of the annual flow between April 2002 and March 2003.

Comparing the data from the low-flow year April 2001 to March 2002 with the high-flow year April 2002 to March 2003, it is interesting to note that the low-flow year was characterized by large changes in the isotopic composition of water with downstream distance. In contrast, the high-flow year was characterized by small changes in the isotopic composition of water with downstream distance (Figure 7).

$\delta^{18}\text{O}$ versus $\delta^2\text{H}$ values. The increase in $\delta^{18}\text{O}$ values with downstream distance within the OMRB (Figure 7) is particularly pronounced in years with low flows. There are three potential explanations for such a trend. Groundwater in the eastern part of the basin has higher $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values than groundwater in western mountainous portion of the watershed. Hence, infiltration of groundwater into the OMR in the eastern part of the basin could potentially explain the trend towards increasing $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values. Another possible explanation is evaporation, which also causes an increase in the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in the remaining non-evaporated water. The third option would be mixing with tributary water having higher $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values than the OMR. This could apply to the OMR stretch between kilometres 120 and 160, due to the influx from the Belly and St Mary Rivers. As will be discussed later, the data suggest that groundwater inflow affects riverine flow within that region. Hence, mixing with tributary water will not be discussed as a separate option but considered under 'groundwater mixing'. The evaluation of both H and O isotope ratios of the water samples is a suitable tool to distinguish between isotopic shifts caused by mixing with groundwater versus those caused by evaporation. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of all groundwater and surface water samples are displayed in Figure 8.

Peng *et al.* (2004) published the following local meteoric water line (LMWL) for precipitation in southern Alberta based on a 9-year record for Calgary (located ~ 150 km north of the OMRB, Figure 1):

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 7.68\delta^{18}\text{O}_{\text{H}_2\text{O}} - 0.21 \quad (r^2 = 0.96, N = 104)$$

Figure 8. $\delta^2\text{H}_{\text{H}_2\text{O}}$ versus $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ plot for OMR samples (open circle), and tributaries (grey diamond). Also shown are: LMWL, the LMWL for Calgary from Peng *et al.* (2004); SWL, regression line for surface water samples collected from the OMRB; GWL, regression line for groundwater samples collected from the OMRB. See Tables I and II for site descriptions

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of almost all groundwater samples plot close to the LMWL (Figure 8). The linear relationship (GWL) between the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of groundwater samples obtained within the OMRB was

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 7.21\delta^{18}\text{O}_{\text{H}_2\text{O}} - 11.91 \quad (r^2 = 0.92, N = 58)$$

The slope of GWL is only slightly lower than that of the LMWL (Figure 8), as the isotopic composition of groundwater is usually comparable to that of local precipitation (e.g. Clark and Fritz, 1997).

Whereas a significant number of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of surface water samples fall close to the LMWL, there are also a significant number of samples, mainly from tributaries, that plot below the LMWL (Figure 8). The linear relationship between the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values obtained from the surface water samples within the OMRB was (SWL)

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 4.05\delta^{18}\text{O}_{\text{H}_2\text{O}} - 64.84 \quad (r^2 = 0.78, N = 420)$$

The slope of the SWL is even lower than the one determined by Kendall and Coplen (2001) for the linear relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of river water samples from Montana (located just south of the OMRB in the northern USA):

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 5.04\delta^{18}\text{O}_{\text{H}_2\text{O}} - 46.48 \quad (r^2 = 0.82, N = 164)$$

The slope of the SWL is also significantly lower than that of LMWL (Figure 8). This is in contrast to the

observation that most of the rivers in the world fall along the meteoric water line, except for those with significant evaporation (IAEA, 2001). Evaporation causes a differential increase in the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of the remaining water, resulting in a lower slope for the linear relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values compared with the slope observed for the LMWL (IAEA, 2001). Within the OMRB, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values from the surface water samples define a linear relationship with a slope of 4.05 compared with 7.68 for the LMWL. Linear relationships between flow-weighted annual average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values for the time period April 2001 to March 2002 for the OMR sites

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 4.91\delta^{18}\text{O}_{\text{H}_2\text{O}} - 50.67 \quad (r^2 = 0.98, N = 5) \quad (1)$$

and the tributary sites

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 3.99\delta^{18}\text{O}_{\text{H}_2\text{O}} - 66.06 \quad (r^2 = 0.87, N = 8) \quad (2)$$

reveal that the slope for the low-flow tributaries often draining irrigated land was somewhat lower than the slope based on isotope data for surface water from OMR sites. Both of these slopes for the linear relationships observed between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values are significantly lower than the one observed for the LMWL and, hence, indicate that evaporation is partially responsible for increasing $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of river water in the eastern part of the basin. Based on the slope of the linear relationship between flow-weighted annual average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values, an average evaporative loss from the OMRB was calculated. The average evaporative loss l

was determined using the following equations from Clark and Fritz (1997), which are based on equations outlined by Gonfiantini (1986) and Majoube (1971). Clark and Fritz (1997) used these to estimate the evaporative loss of groundwater in northern Oman:

$$\text{average evaporative loss } l = 100[1 - \exp(f)]$$

where f is the residual water fraction

$$\Delta\delta^{18}\text{O} = \varepsilon^{18}\text{O}_{\text{total}} \ln(f)$$

where $\Delta\delta^{18}\text{O}$ is obtained from Figure 9

$$\varepsilon^{18}\text{O}_{\text{total}} = \varepsilon^{18}\text{O}_{v-l} + \Delta\varepsilon^{18}\text{O}_{v-bl}$$

(equal to equilibrium plus kinetic enrichment factors)

$$\varepsilon^{18}\text{O}_{v-l} = -11.2\text{‰}$$

which is based on mean annual $T = 4.5^\circ\text{C}$ within the OMRB, and

$$\Delta\varepsilon^{18}\text{O}_{v-bl} = -14.2(1 - h)$$

(the kinetic enrichment factor) where h is humidity, based on the slope of the linear relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values.

Taking a slope of 4.5 for the linear relationship between flow-weighted annual average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values within the OMRB, $h \approx 0.5$. Based on Figure 9, $\Delta\delta^{18}\text{O} \approx 2 \pm 1\text{‰}$, which is the shift in $\delta^{18}\text{O}$ values between upstream and downstream water samples. Hence, the average evaporative loss l within the

Figure 9. Flow-weighted annual average $\delta^2\text{H}_{\text{H}_2\text{O}}$ versus $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ plot for OMR samples (black diamond), and tributaries (open square) from April 2001 to March 2002. Also shown are: LMWL, the LMWL for Calgary from Peng *et al.* (2004); SWL, regression line for all surface water samples collected from the OMRB; Equations (1) and (2) (see text for explanation). See Tables I and II for site descriptions

central and eastern regions of the OMRB is around $10 \pm 5\%$. This is considered a lower limit, since the method used to estimate evaporative loss does not account for water that evaporates totally or is otherwise disconnected from runoff. For the most eastern part of the basin, the estimated average evaporative loss is most likely also a conservative estimate, as samples from that region plot along a line of slope ~ 2.7 (Figure 9, inset).

Evaporative loss can occur during groundwater recharge, within reservoirs, and in-stream. The data presented indicate that some evaporation does occur during the recharge process, as the GWL has a lower slope than the LMWL (Figure 9). This is in agreement with Hendry (1988), who observed a linear relationship with a slope of 6.0 between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of groundwater samples from till in southern Alberta:

$$\delta^2\text{H}_{\text{H}_2\text{O}} = 6.0 \delta^{18}\text{O}_{\text{H}_2\text{O}} - 39.3 \quad (r^2 = 0.92, N = 84)$$

Evaporation also occurs within the OMR reservoir, as the flow-weighted annual average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values measured at kilometre -33 and kilometre 6 plot along a line having a slope close to 4.5 (Figure 9, inset). Between kilometre 6 and kilometre 171, the data suggest that groundwater exchange controls the isotopic composition of water (tributary and main stem), as samples plot along the GWL (Figure 9, inset). Downstream of kilometre 171, $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values plot along a line of slope ~ 2.7 for both the OMR and tributary sites (Figure 9, inset). This is indicative of strong evaporation, either in-stream, in reservoirs, or during irrigation and groundwater recharge in the irrigation districts. Discerning the relative importance of in-stream evaporation versus return flow of evaporated irrigation water was not possible with the current dataset, as irrigation water and recharging groundwater under irrigated fields was not analysed during this study.

CONCLUSIONS

The analysis of the stable isotope composition of water in conjunction with hydrometric data provided further insight into the water dynamics of the OMRB. High flows occurred during the spring–summer, coinciding with snowmelt and occasional heavy rains. The isotopic composition of water, however, was not characterized by a marked shift towards lower values indicative of winter precipitation during peak flow. This indicates that young groundwater is a major contributor to peak runoff in the western headwater portion of the basin. Hence, groundwater influx has a major control on riverine flow within this basin. Furthermore, $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values indicate that evaporation affects water resources within the eastern region of the OMRB with an average evaporative loss for this basin estimated at a lower limit of $10 \pm 5\%$.

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