JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 13 2005

STABLE OXYGEN ISOTOPE HYDROLOGY AND SLOW BASIN RESPONSE IN AN OLD-GROWTH FORESTED CATCHMENT, WOLF RIVER BASIN, WISCONSIN

Erik B. Melchiorre — Department of Geological Sciences, California State University San Bernardino, USA

Robert E. Criss — Department of Earth & Planetary Science, Washington University, USA

Oxygen isotope variations of the Wolf and Red Rivers, Wisconsin are very small (1 to 5‰ variation) compared to those of local meteoric precipitation (25‰ variation), with behavior that may be modeled using published isotope hydrology equations based upon time-decay damped-storage, indicating that stream flow is a damped running average of local meteoric precipitation that has been stored and homogenized in shallow groundwater reservoirs for 0.34 to 1.1 years. These residence times are long for most small rivers (<1000 cfs) in the Midwestern USA and likely reflect the high proportion of old growth forest and wetlands within the watershed. Deviations from the damped average model are largely caused by melting of accumulated snowfall during spring. Small decreases in the ^{18}O content of precipitation and of streamflow accompany increase in elevation in the basin. The average $\delta^{18}O$ values of the rivers and the specific conductance of river baseflow are similar to shallow groundwaters from nearby wells.

INTRODUCTION

Geochemical studies utilizing chemical (Pinder and Jones, 1969), specific conductance (Pilgram et al., 1979), and stable isotope data (Sklash and Farvolden, 1979) demonstrate congruently that river flow in most regions is dominated by groundwater, even during periods of normal but not extraordinary flooding (e.g., Winston and Criss, 2002). Oxygen and hydrogen isotope data have proven to be one of the most versatile and useful techniques for examining rivers and determining the degree to which ground and surface waters interact. Many isotope studies have revealed that a significant component (50-100%) of storm runoff is expelled groundwater (Mook et al., 1974; Fritz et al., 1976; Sklash et al., 1976; Sklash and Farvolden, 1979; Hooper and Shoemaker, 1986; Pearce et al., 1986; Frederickson and Criss, 1999). Most such studies divide waters into "event water" such as overland flow and "pre-event water" such as baseflow so that simple mass balance arguments may be used to determine their relative abundances. Moreover, a constant isotope value is typically assumed for the pre-event water that is commonly considered to be identical to local groundwater. However, Rose (1996) has shown that baseflow is more isotopically variable than groundwater and can be derived from a shallow reservoir with little new rain. Furthermore, in regions of significant winter snow accumulation, it has been demonstrated that kinetic processes during snow metamorphism and melting may enrich recharge melt waters (Rose et al., 1999).

In this study we present a 2-year stable isotope record of the Wolf and Red Rivers of the Wolf River Basin of central Wisconsin. We apply the "damped running average" model of Frederickson and Criss (1999) to demonstrate that stream flow in these rivers has surprisingly long residence times that likely reflect the high proportion of undisturbed old growth forest in the basin.

THE WOLF RIVER BASIN

Regional Geography, Geomorphology, and Geology

The Wolf River Basin is one of the largest watersheds in Wisconsin, and drains over 7000 km^2 in all or parts of 11 counties (Figure 1). The Wolf River originates at Pine Lake, and empties into the Fox River just 8 km west of Lake Winnebago and the city of Oshkosh, WI. The Red River is a major tributary of the Wolf River. The Wolf-Red watershed is a nearly homogenous basin with respect to principal land cover and geology (Shafer et al., 1997). Land use within the basin is approximately 70% forest, 15% natural wetlands, 14% agriculture, and less than 1% urban (e.g., Olcott, 1968; Shafer et al., 1997). Within the forested sections, a thriving logging industry is dominated by the sustainable tree harvesting program of the 1000 km^2 Menominee Tribe Reservation, encompassing significant stands of old growth forest and undisturbed wetlands.

Topography of the basin is dominantly controlled by the bedrock surface, with local modification by glacial deposits. Drainage topography ranges from over 550 meters (1800 feet) above sea level in the northern headwaters to 225 meters (741 feet) at the confluence with the Fox River (Figures 1 and 2). The Wolf River has a steep gradient from the headwaters to Shawano, falling about 262 meters (860 feet) over 87 km (54 miles), while from Shawano to the confluence with the Fox River the gradient is only 17 meters (56 feet) over 183 km (114 miles). The gradient of the Red River is about 45 meters (148 feet) over 40 km (25 miles).

The bedrock geology of the basin (Figure 3) is dominated by Proterozoic granitic rocks of the Wolf River batholith, which intrudes earlier Proterozoic metamorphic and igneous rocks of the

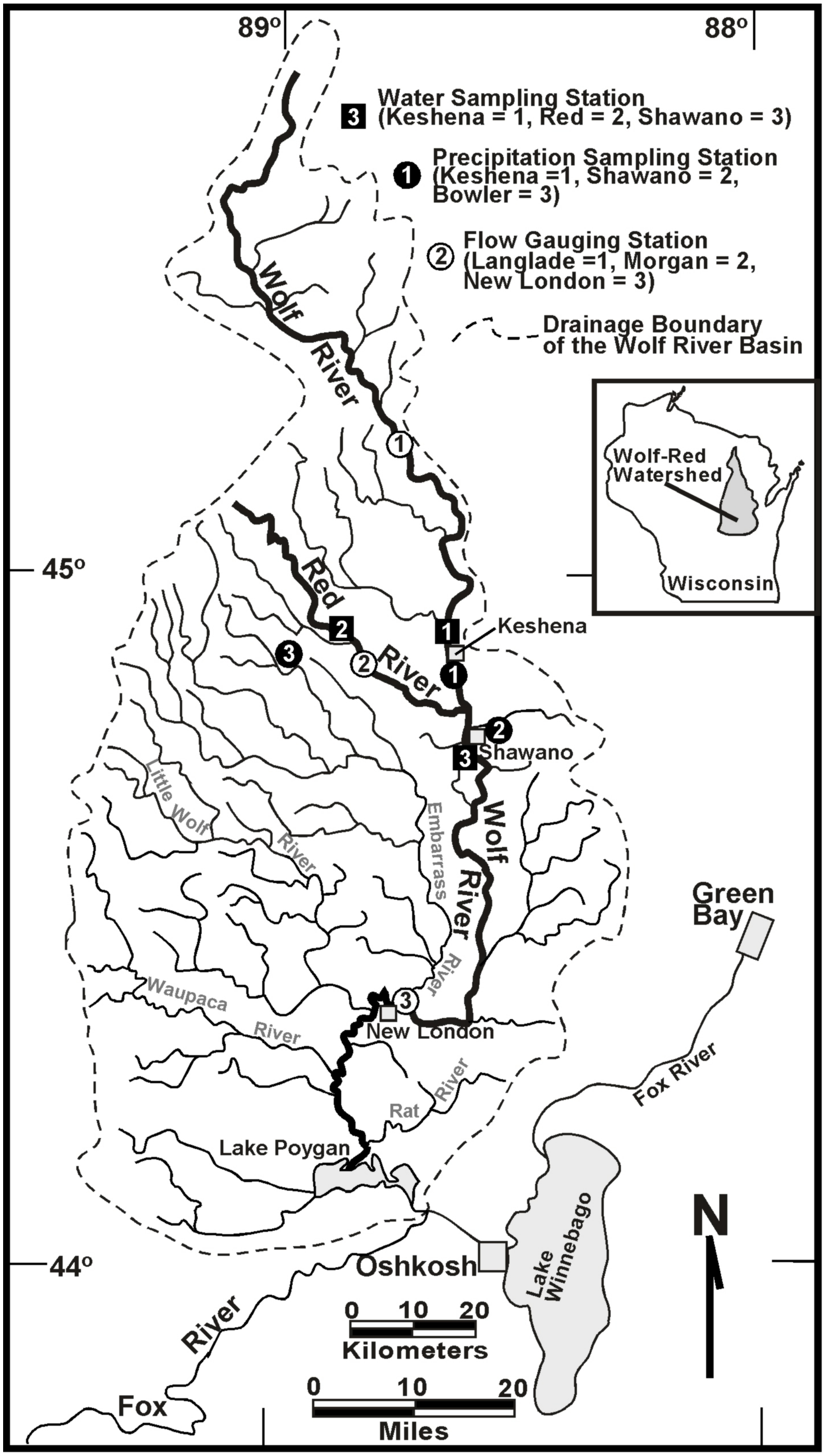

Figure 1. Index map of the Wolf River basin showing the location of river sampling stations (black squares), precipitation sampling stations (black circles), and USGS streamflow monitoring stations (open circles).

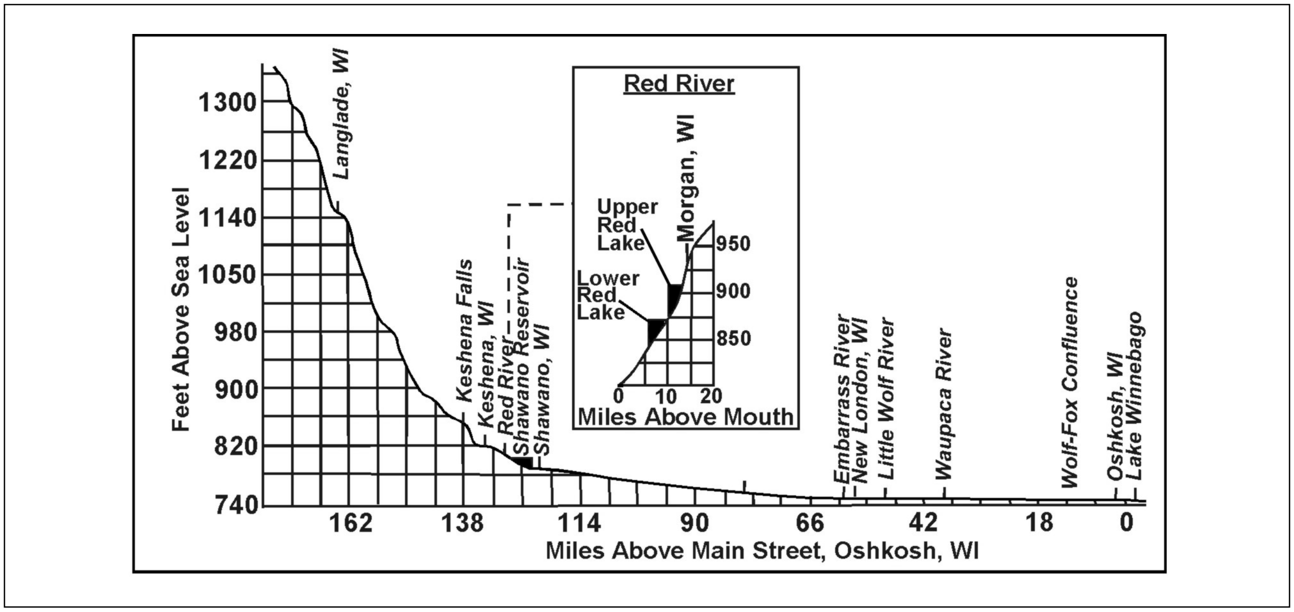

Figure 2. Cross-section of gradient for a portion of the Wolf and Red Rivers (after Olcott, 1968). Black filled areas show length and depth of impoundments.

Wisconsin Magmatic Terrain (e.g., Bean, 1949; Van Schmus et al., 1998). South of New London, the Wolf River flows through Cambrian sandstones and Ordovician sedimentary rocks that comprise the southern- and eastern-most portion of the basin. These sedimentary rocks generally dip gently to the southwest.

The bedrock is overlain by an average of 6 to 27 meters (20 to 90 feet) of glacial deposits, though south of New London the deposits are at least 60 meters (200 feet) thick where they fill a pre-glacial valley in the bedrock. Glacial deposits are dominantly recessional, outwash, and ground moraine in the north, ground moraine in the central portion, and glacial lake deposits in the south and east (Figure 4).

Precipitation and Climate

The Wolf-Red watershed received an annual average of 81 cm (32 inches) of precipitation during the period 1931 to 2000 (Waite, 1960; NOAA File Data, 2000). Deviation from these long-term mean values can be extreme, ranging from 114 cm (45 inches) in 1942 to 48 cm (19 inches) in 1958. In a typical year precipitation is highest in late winter and early spring, decreases through late spring and summer, slightly increases in fall, then drops into winter until the cycle starts anew. The peak river flow usually occurs in the early spring due to snowmelt. Daily mean air temperature extremes range from winter lows of –26ºC (-15ºF) to summer highs of 32ºC (90ºF) (NOAA File Data, 2000). The average evapotranspiration within the basin is 56 cm (22 inches) per year (Olcott, 1968). Evapotranspiration is significant during summer but virtually stops after temperatures begin to regularly drop below freezing. During winter, precipitation is stored on land as snow and ice, with abundant runoff and infiltration in spring from melting and rainfall. In summer as precipitation wanes, evapotranspiration increases, leaving less water for infiltration and runoff.

Hydrology

Most of the upper Wolf River basin is old growth forest sustainably managed by Menominee Tribal Enterprises, the Stockbridge Tribe, and the US Forest Service. The only

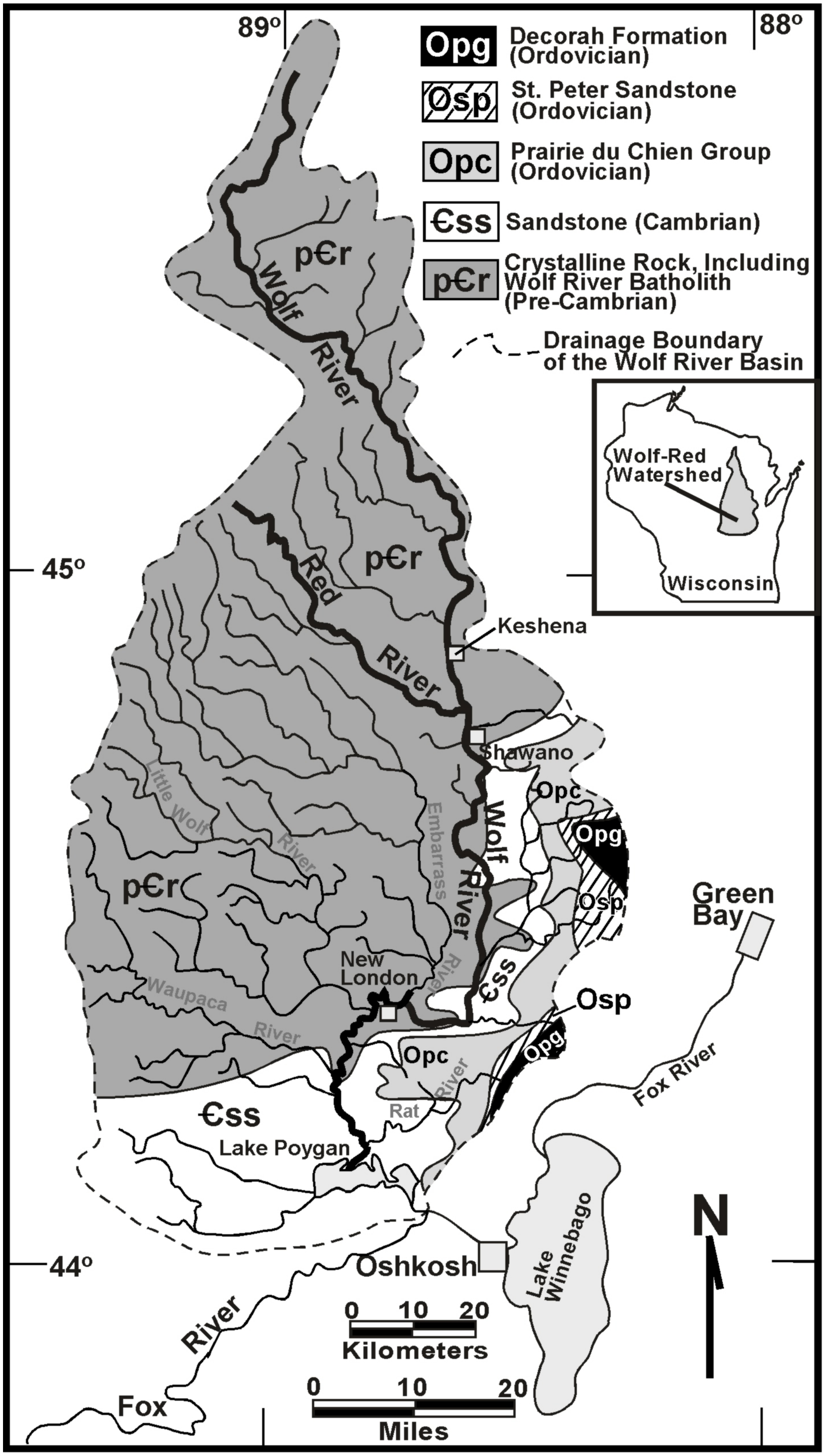

Figure 3. Bedrock geology of the Wolf River basin.

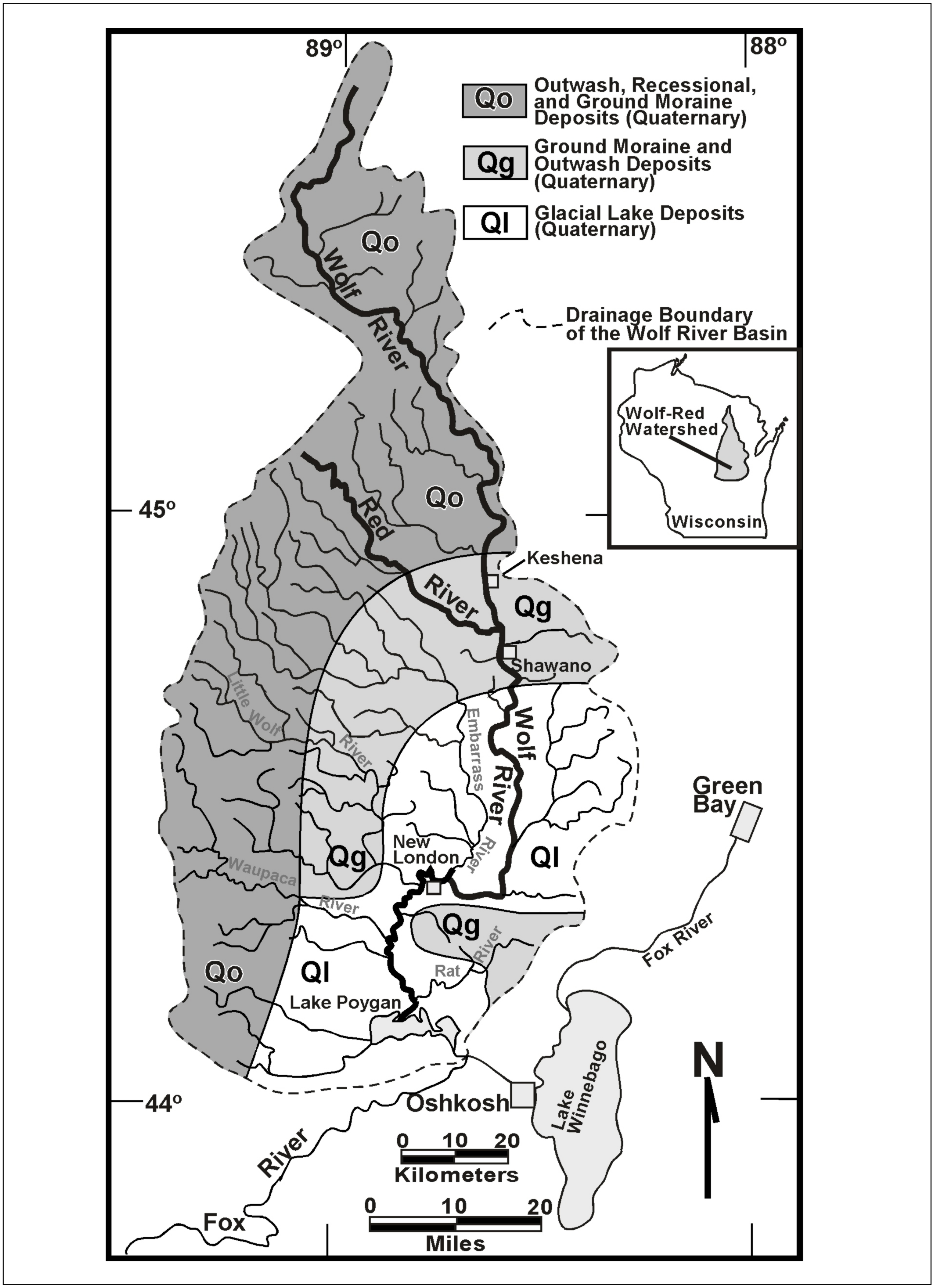

Figure 4. Glacial and surficial deposits of the Wolf River basin.

significantimpoundment on the Wolf River is Shawano Reservoir which has small storage, and is a "run of river" impoundment, producing a low impact on the river as required by the Menominee Tribe to sustain the recovering sturgeon population. Our sampling at the Wolf River Keshena site is well above the Shawano impoundment. Some small natural lakes related to glacial features are located in the northern headwaters of the Wolf River. The Red River also has small lakes in its headwaters. Several miles below the Red River Morgan sampling site, the Red River has two small "run of river" hydroelectric impoundments that slightly modify flow.

Flow variations on the Wolf and Red Rivers are much smaller than those typical for rivers of comparable size, with the flows being highest after periods of rainfall and following spring snowmelt. For example, over the two-year period of study the Wolf River at Shawano varied only from 500 to 3200 cfs, a factor of only 6.4. These small variations must result from the nature of the shallow subsurface, land use, and the long residence time indicated by the stable isotope data (see below). While land use patterns vary across the basin, forests and natural wetlands dominate over 80% of the watershed (e.g., Olcott, 1968; Shafer et al., 1997).

Glacial drift aquifers are believed to be the principle source of groundwater discharge to streams of the Wolf Basin, based upon the similarity of water quality and chemistry between surface waters and wells in glacial deposits (Olcott, 1968). Aquifer hydraulic conductivities (K) been measured at between 2.0 and 6.3 cm/hr (0.8 and 2.5 inches/hr) (Olcott, 1968; Shafer et al., 1997; Shawano Water District Open File Data, 2000). These thin (6 to 27 m) glacial aquifers have only modest storage capacity, and their K-values suggest some interbedded silt may be present. The groundwater hydraulic gradient is steep in the north of the basin but flattens out south of Shawano due to increased discharge to rivers and wetlands, as well as thickening of the glacial aquifers (e.g., Harder and Drescher, 1954; Berkstresser, 1964). The idea that local groundwater moves from areas of high head to low head and drives stream and river discharge though baseflow in the Wolf Basin was first proposed by Olcott (1968).

Water Chemistry

Groundwater from glacial drift aquifers of the Menominee Reservation average 42 ppm Ca, 18 ppm Mg, 3 ppm Na, 216 ppm HCO_3, 2 ppm SO_4, a pH of 7.6, and a specific conductance of 285 mS (Olcott, 1968; Menominee County Environmental Office, file data). The Wolf River at Keshena Falls averages 33 ppm Ca, 17 ppm Mg, 2 ppm Na, 132 ppm HCO_3, 7 ppm SO_4, a pH of 7.4, and a specific conductance of 240 mS (Olcott, 1968; Menominee County Environmental Office, file data). In general, total dissolved solids (TDS) in waters of the northern reaches of the basin are 175 to 300 ppm for groundwater, and 100 to 200 ppm for surface water. In the central portion of the basin, groundwater and surface waters both average 200 to 400 ppm TDS. Groundwater averages 300 to 500 ppm TDS in the southern reaches of the basin, while surface waters average 350 to 400 ppm TDS (Olcott, 1968). The Wolf River at Langlade, 48 km north of the Keshena Falls, has a pH of 7.9 to 8.5, and a specific conductance of 109 to 193 (Shafer et al., 1997). Measurements of specific conductance are often used to distinguish ground and surface water sources. The Wolf River displays an inverse relationship between discharge and specific conductance (Shafer et al., 1997), suggesting dilution of baseflow ground water by surface waters during spring melt runoff and large precipitation events. Relationships between dissolved organic carbon, specific conductance, and discharge suggest that surface waters of the Wolf Basin and similar basins to the north in Canada may be transported to rivers through subsurface baseflow (Wallis, 1979; Hendershot et al., 1992; Peters et al., 1995).

METHODS

Both storm and intra-storm river, well, and precipitation samples were collected in borosilicate glass sample bottles with polyseal caps to prevent evaporation. Sampling was performed as frequently as conditions and scheduling permitted. Samples from the Wolf River were collected at Keshena Falls on the east side of the bank just north of the bridge, from a prominent granite outcrop. The Wolf River at Shawano was sampled from the center of the State Route 22 bridge south of town, using a stainless steel bailer lowered on a rope. The Red River was sampled on the eastern bank just south of the Indian Route 22 (I.R. 22) bridge. In the winter, an axe or gasoline-powered ice auger was used to access the river waters through up to 4 inches of ice at the Keshena Falls and Red River sites. The Wolf River at Shawano did not completely ice over during this study, and was sampled through available holes in the ice under the bridge.

Precipitation samples were collected from standard US Forest Service style rain gauges modified with a hollow plastic float ball in the collection cone to minimize evaporation. Samples were regularly collected from gauges located at the Collage of Menominee Nation on the Menominee Reservation in Keshena, the Stockbridge Reservation Environmental Office near Bowler, and the lead authors residence adjoining Shawano airport (Figure 1). Precipitation was collected within several hours of the storm end, in order to minimize evaporation. All precipitation for each half-month time period was collected, mixed, and stored within a large borosilicate glass bottle with a polyseal cap. At the end of each semi-monthly period, an aliquot of this bottle was removed for analysis, providing a volume-weighted precipitation composite for the time period.

Field measurements of specific conductance (mS) were performed using a portable YSI field meter, while river temperature was taken every 4 hours by on-site automated data loggers installed in vandal-proof boxes located at the sampling stations. River temperature data is reported in this study as daily mean. Air temperature data was collected every 10 minutes using a Davis Weathermonitor II station installed at the College of Menominee Nation, and is also reported here as a daily mean. Stream flow data was collected from the US Geological Survey stations located on the Wolf River at Langlade (USGS station # 04074950), the Wolf River at New London (USGS station # 04079000), and the Red River at Morgan (USGS station # 04077630) (Figure 1), and is archived at http://water.usgs.gov/wi/nwis/.

Water samples were prepared using the standard CO_2 equilibration method (Epstein and Mayeda, 1953), and oxygen isotope values were measured using an automated sample equilibrator interfaced with and isotope ratio mass spectrometer. Results are reported in the usual d-notation relative to V-SMOW. Laboratory precision is ±0.05‰ for oxygen isotope values.

RESULTS

Precipitation

Monthly precipitation at Shawano ranged from 17.8 cm (7.04 inches) to 0.4 cm (0.15 inches) during the study period (Figure 5). The $d^{18}O$ values of bimonthly precipitation composites ranged from -3.95 to -28.41‰, with a simple average of -11.89 and a weighted average of -9.55‰. Comparison data from Bowler and Keshena, Wisconsin show that spatial variation in precipitation amounts and isotope values is small, although the weighted average $d^{18}O$ value at Bowler is slightly lower at -9.85‰, partly due to its 70m higher elevation (Figure 2). Unless otherwise stated we use the Shawano precipitation data in the following calculations.

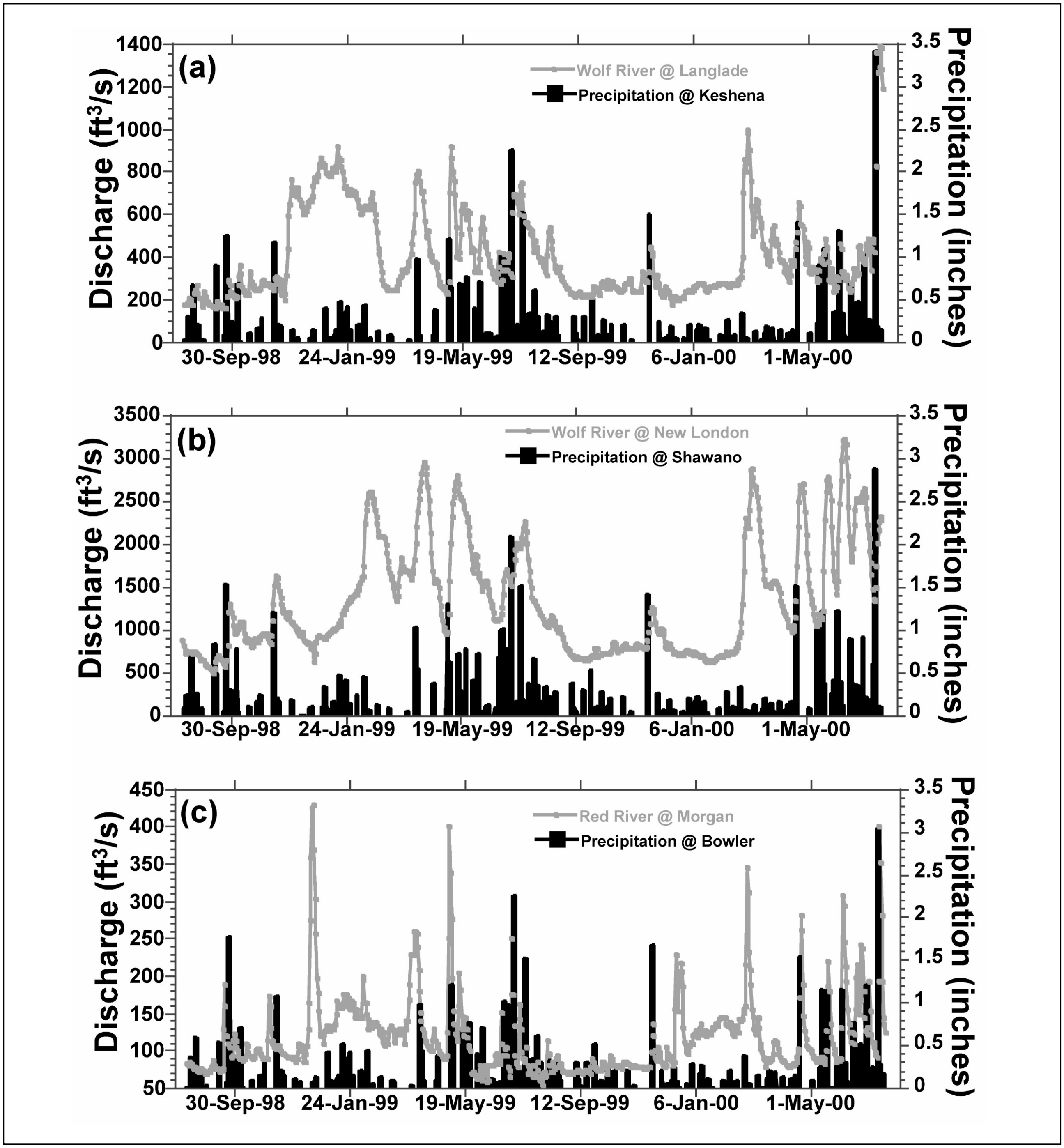

Figure 5. Discharge (gray curve and dots) and precipitation (black bars) for the Upper Wolf River at Keshena Falls (a), Lower Wolf River at Shawano (b), and Red River at Morgan (c) over the period of this study. Locations of the discharge and precipitation sampling sites are shown in Figure 1.

River Discharge

The mean daily discharge for the Wolf River at Langlade during the period of this study (August 1998 to July 2000) was 11.5 m^3/s (406 cfs), with a peak daily discharge of 39.4 m^3/s (1390 cfs) on 1/23/99 and a minimum daily discharge of 4.5 m^3/s (159 cfs) on 9/23/98. The mean daily discharge for the Wolf River at New London was 38.0 m^3/s (1343 cfs), with a peak daily discharge of 91.5 m^3/s (3230 cfs) on 4/19/99 and a minimum daily discharge of 14.2 m^3/s (500 cfs) on 9/13/98. The mean daily discharge for the Red River at Morgan was 3.3 m^3/s (118 cfs), with a peak daily discharge of 12.2 m^3/s (430 cfs) on 12/18/98 and a minimum daily discharge of 1.6 m^3/s (55 cfs) on 5/8/99. Discharge for the period of this study is shown in Figure 5.

Temperature

Air temperatures at Keshena exhibit a normal sinusoidal cycle about the annual average near 7°C (45°F) (Fig 6). Water temperatures approximate air temperatures during most of the year, except they bottom out near 0°C during winter freeze (Figure 6).

Specific Conductance

The specific conductance of the Wolf River at Keshena Falls during the period of this study averaged 230 mS, with a maximum of 390 mS on 9/24/98 and a minimum of 101 mS on 12/21/98(Figure 7). The specific conductance of water in the Wolf River at Shawano averaged 247 mS, with a maximum of 355 mS on 12/19/99 and a minimum of 101 mS on 7/15/00. The specific conductance of water in the Red River at the I.R. 22 bridge averaged 288 mS, with a maximum of 365 mS on 7/3/99 and a minimum of 201 mS on 7/9/00. Well waters have an average conductance of 361 mS in the upper Wolf River sub-basin, and an average conductance of 563 mS in the Red River sub-basin (Table 1).

Stable Isotope Data

The average $d^{18}O$ value of water in the Wolf River at Keshena Falls during the study was -10.22‰, with a maximum of -7.8‰ on 7/22/99 and a minimum of -12.5‰ on 5/6/00. The average $d^{18}O$ value of water in the Wolf River at Shawano was -9.78‰, with a maximum of -8.0‰ on 7/12/99 and a minimum of -11.7‰ on 4/21/00. The average $d^{18}O$ value of water in the Red River at the I.R. 22 bridge was -10.51‰, with a maximum of -9.3‰ on 7/19/99 and a minimum of -11.9‰ on 5/21/99. Well waters in the upper Wolf River sub-basin have an average $d^{18}O$ value of -9.50‰, and in the Red River sub-basin an average $d^{18}O$ value of -10.79‰. Isotope values for the period of this study are shown in Figure 8. Note that while both river and precipitation values show seasonal variation, the magnitude of the precipitation $d^{18}O$ value variation is much larger than that for local rivers.

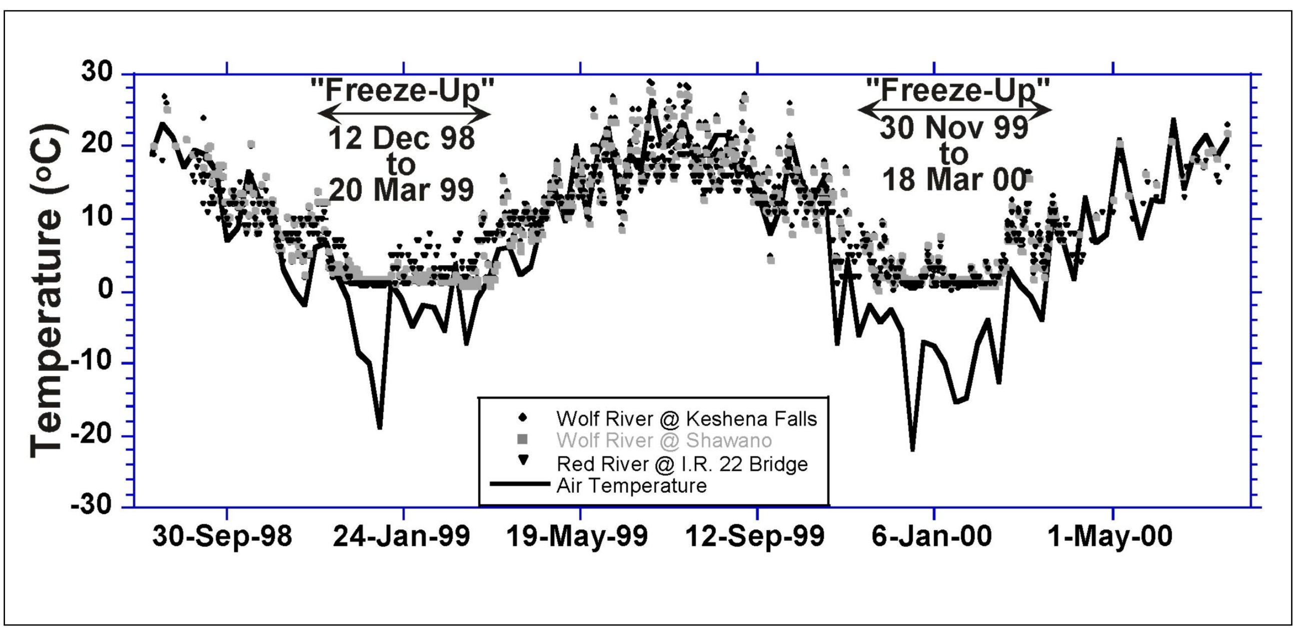

Figure 6. Temperature of river waters and air over the period of this study.

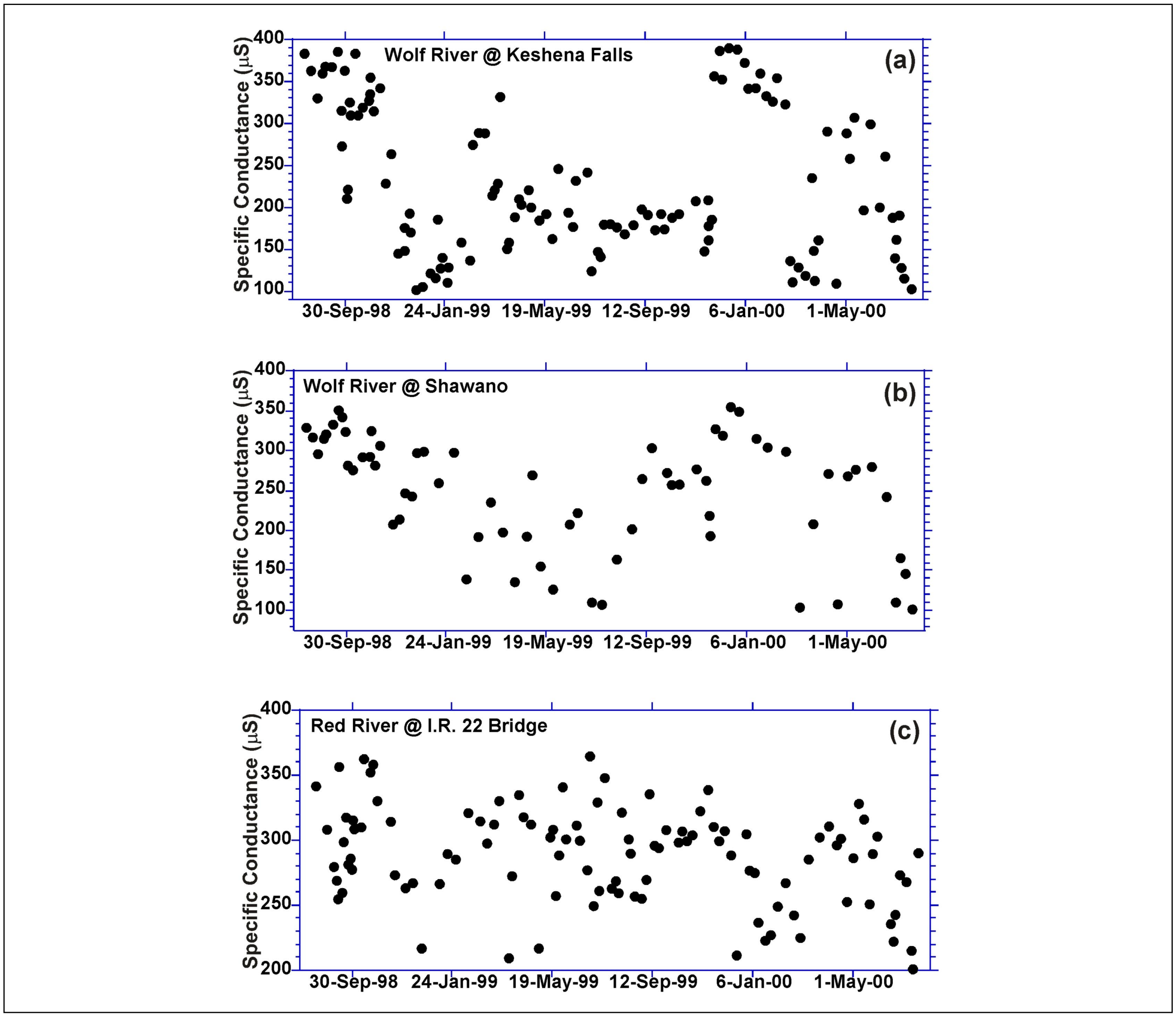

Figure 7. Specific conductance of river waters of the Upper Wolf River at Keshena Falls (a), Lower Wolf River at Shawano (b), and Red River at Morgan (c) over the period of this study.

Table 1. Geochemical and Isotopic Data for Well Waters in the Catchment of the Wolf and Red Rivers

Well Location	[1]Closest River	Cond. (µS)	pH	Ca^{2+} (ppm)	Mg^{2+} (ppm)	HCO_3^- (ppm)	Cl^- (ppm)	Na^+ (ppm)	K^+ (ppm)	SO_4^- (ppm)	Nitrate (ppm)	Fe (ppm)	$\delta^{18}O$ (SMOW)
T.28N, R.16E, Sec.22, qtr.A	Wolf	380	6.7	73	36	268	8	6	1.5	9	0.5	1.9	-9.60
T.29N, R.14E, Sec.19, qtr.E	Wolf	418	6.8	67	32	244	53	34	1.0	5	1.0	0.2	-9.57
T.28N, R.15E, Sec.24, qtr.L	Wolf	379	6.7	60	29	219	14	10	1.0	6	0.6	0.4	-9.23
T.22N, R.15E, Sec.24, qtr.M	Wolf	309	7.1	43	21	158	12	7	1.0	4	0.3	0.3	-9.46
T.28N, R.15E, Sec.22, qtr.G	Wolf	319	6.5	60	29	219	14	9	1.0	3	0.9	0.2	-9.66
T.27N, R.14E, Sec.19, qtr.H	Red	622	7.0	83	40	305	18	12	1.5	8	9.5	0.1	-10.72
T.27N, R.14E, Sec.36, qtr.E	Red	551	6.9	80	39	293	15	10	1.0	7	8.0	0.2	-10.68
T.28N, R.13E, Sec.1, qtr.A	Red	530	7.0	-	-	-	-	-	-	-	-	-	-10.87
T.28N, R.13E, Sec.3, qtr.C	Red	569	8.0	-	-	-	-	-	-	-	-	-	-10.74
T.29N, R.13E, Sec.13, qtr.E	Red	542	7.0	-	-	-	-	-	-	-	-	-	-10.92
Wolf River Well Averages:		361	6.8										-9.50
Red River Well Averages:		563	7.2										-10.79
ALL DATA AVERAGES:		**462**	**7.0**	**67**	**32**	**244**	**19**	**13**	**1.1**	**6**	**3.0**	**0.5**	**-10.15**
1Catchment that well lies within.													

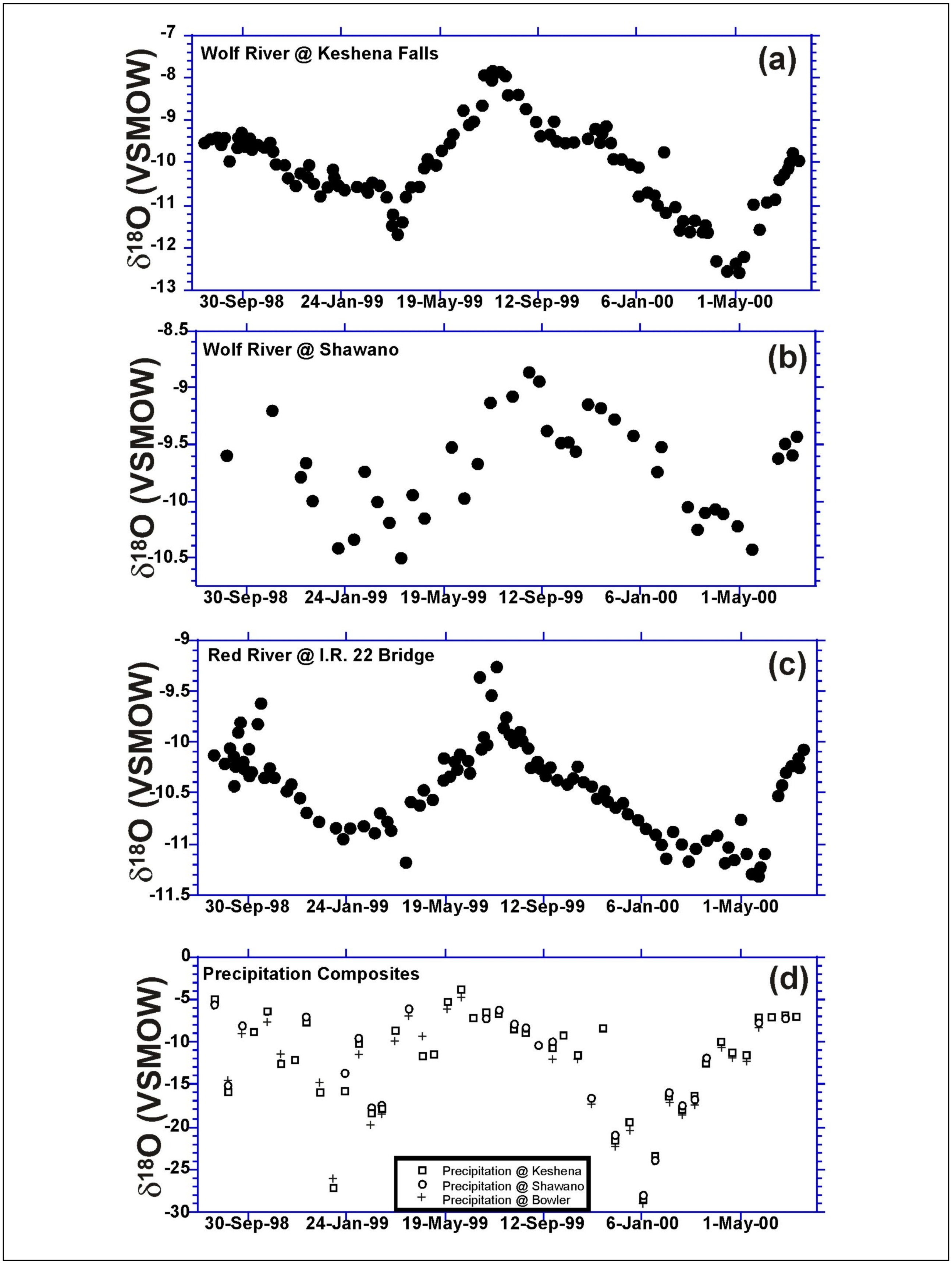

Figure 8. Stable oxygen isotope values of river waters of the Upper Wolf River at Keshena Falls (a), Lower Wolf River at Shawano (b), Red River at Morgan (c), and precipitation composites (d) over the period of this study.

DISCUSSION

Precipitation and River Discharge

Measured river discharge can be linked to three factors: Precipitation measured at monitoring stations, precipitation within the basin but not recorded at the monitoring stations, and spring season melting and river ice breakup (Figure 6). A general correlation is observed between measured precipitation and discharge. Several examples of precipitation-related increases in river discharge are observed for the period May to September, 1999 (Figure 5). At some stations during this period the magnitude of the precipitation and discharge record are inconsistent with other events pairs and occasionally there is little recorded precipitation before an increase in river discharge. It is assumed that this effect is caused by the limited precipitation monitoring stations within the basin, and the resulting statistical bias for storms that do not pass over a station. Elevated discharge from spring melting and river ice breakup is evident in mid-March (see Figure 6 for dates) of 2000, while precipitation in mid-March of 1999 slightly masks the increase in discharge (Figure 5). The river "freeze-up" at the station at Langlade produced artificially elevated discharge in the period December 1998 to February 1999 (Figure 5). A similar spike in discharge related to the first ice on the river was also observed for a few days in December on the Red River. This "ice effect" on discharge of shallow and narrow rivers is well documented in Wisconsin and Minnesota (USGS, 2000).

River Discharge and Specific Conductance

Specific conductance of river water is strongly linked to discharge at all three stations (Figure 9). The Wolf River at both Keshena Falls and Shawano show a modest range of specific conductance values, from 100 to over 350 mS, while the Red River is limited to the range 200 to slightly over 350 mS. This may indicate that the Wolf River is more susceptible to precipitation-induced dilution, while the Red River is more influenced by displacement of higher-conductance groundwaters by precipitation. These small variations in conductance with respect to other rivers of similar size suggest the dominance of baseflow in the Wolf and Red Rivers.

Stable Isotope Values

Frederickson and Criss (1999) developed a "dampened average" model to predict the $\delta^{18}O$ value of river water from the $\delta^{18}O$ value and amount of precipitation. The model is:

$$\delta^{18}O_{flow} = \frac{\sum \delta_i P_i e^{-t_i/\tau}}{\sum P_i e^{-t_i/\tau}} \qquad \text{(Frederickson and Criss, 1999)} \qquad (1)$$

where δ_i and P_i are the $\delta^{18}O$ value and amount for a given precipitation event, t_i is the time interval between precipitation and sampling of the river, and t is the time constant for the site. A large value for t indicates that river baseflow has been homogenized for a long period of time in a large groundwater reservoir. For a small value of t the $\delta^{18}O$ value of river flow is very similar to recent precipitation, because storage is small and all but the most recent events are damped out by the exponential term.

Using precipitation $\delta^{18}O$ values from the Shawano monitoring station (Figure 1), the damped average equation (1) may be used to calculate isotopic values for the local river that closely simulate the measured values (Figure 10). The lack of a perfect match between observed values and the model may result from snowmelt, enrichment by partial sublimation, and other kinetic processes.

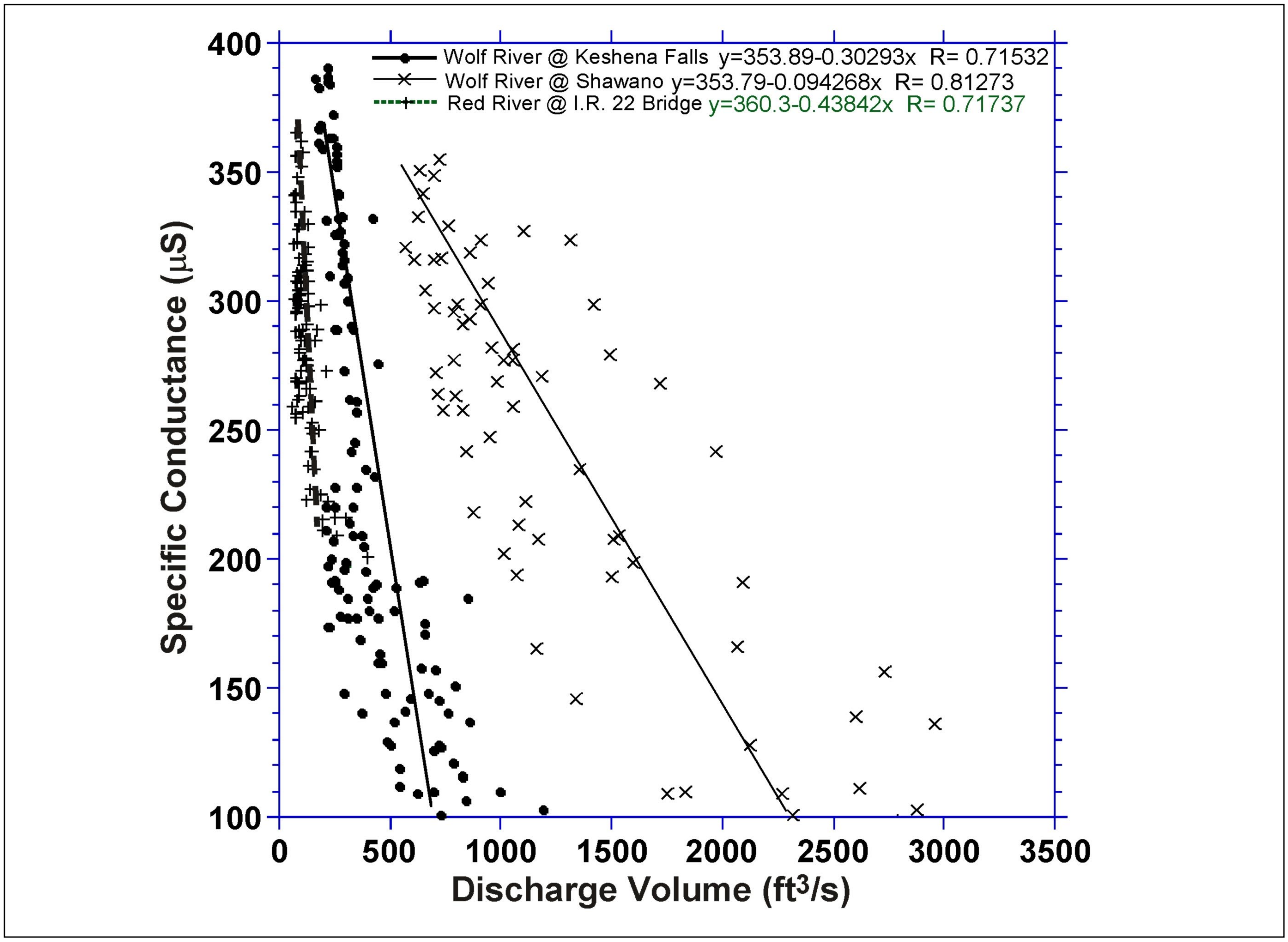

Figure 9. Relationship between discharge and specific conductance for the Wolf and Red River sampling sites.

For the Wolf River at Keshena Falls, the best fit of this calculated curve to the measured values is obtained with a value of t = 0.34 years (Figure 10a). This value of t is similar to, but slightly larger than the values used to predict behavior on the Meramec and Big Rivers of Missouri (Frederickson and Criss, 1999). This higher value suggests relatively slow recharge of baseflow from precipitation, probably from the shallow glacial aquifers that dominate the upper catchment of the Wolf River (Figure 4).

The calculated $\delta^{18}O$ values for the Wolf River at Keshena Falls differs from the observed values by up to 1‰ in the fall and winter. In winter, precipitation accumulates as snow and ice. Rose et al. (1999) documented that snow meltwater may become enriched through evaporation during ablation and infiltration. This phenomenon, and the delayed release of large volumes of meltwater, may explain why the model overestimates river $\delta^{18}O$ values in February and March for 1999 and 2000, the periods when river ice is breaking up and snow melt is at its peak (Figure 6). It is not clear why the model overestimates $\delta^{18}O$ values during the period September to October, 1999.

Limited isotope data are available for the Wolf River at Shawano (Figure 10b), however $\delta^{18}O$ values calculated from precipitation fit well with the river measurements when a t value of 1.1 years is used in the damped average model equation (1). This t value is much larger than for other rivers in the Midwestern US, and corresponds to t values observed for springs (Frederickson and Criss, 1999). This may indicate that the river receives significant baseflow from older, homogenized groundwaters.

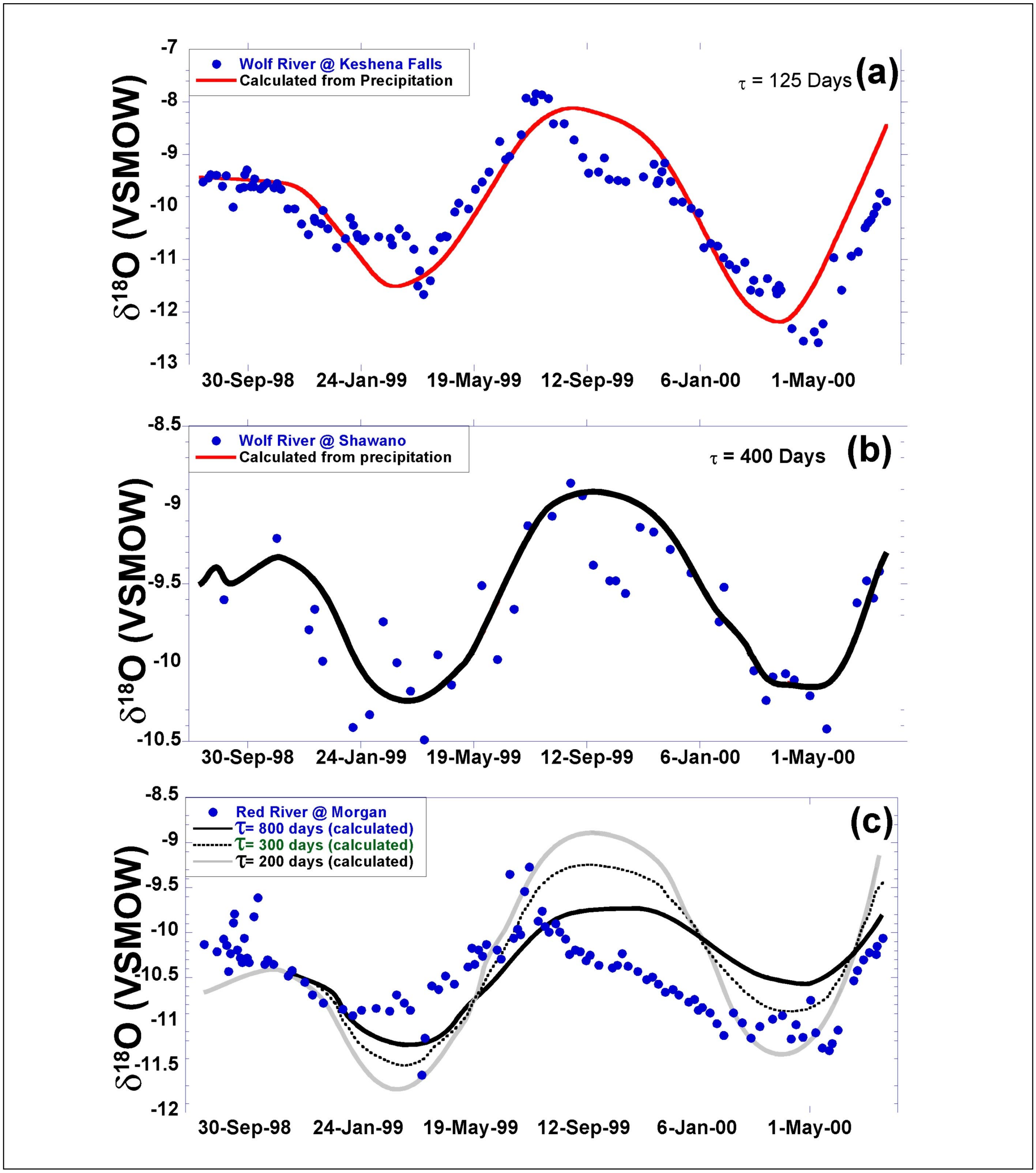

Figure 10. Stable oxygen isotope values of river waters and damped average model estimations of the Upper Wolf River at Keshena Falls (a), Lower Wolf River at Shawano (b), Red River at Morgan (c) over the period of this study.

The isotope behavior of the Red River is well described by the damped average equation (1), except that this river is systematically ~0.7 permil lighter than the Wolf River at Shawano. As precipitation in the upper Red River basin is slightly lower in ^{18}O than the average for the Wolf basin above Shawano, an offset of 0.7 permil has been applied to the calculated curve (Figure 10c) for the Red River. The large t value of 1.0 year (Figure 10c) suggests that the Red River also receives significant baseflow from very homogenized waters.

THE IMPACT OF LAND USE ON THE HYDROLOGY OF THE WOLF RIVER BASIN

Little of the Midwestern US has remained undisturbed since pre-Columbian times. Virtually the only such area of considerable size is the Menominee Native American Reservation of Central Wisconsin. This reservation, and several smaller adjoining reservations, retains largely unmodified lands and large stands of essentially old-growth forest that clearly define reservation boundaries even when viewed in aerial photographs and satellite images. The sustainable harvesting of selected hardwood trees by Menominee Tribal Enterprises has minimal impact upon the forest. Less than 15% of the Basin has been modified for agricultural or urban use. Thus, the largely undamed and unlogged Wolf and Red Rivers provide as close a glimpse of unmodified drainage basin behavior as can be found in the Midwestern USA.

Stable isotope evidence demonstrates that waters of the Wolf and Red Rivers have residence times much larger than for similar rivers elsewhere in the Midwestern US. We suggest that these larger residence times result from the effects of old-growth forest canopy interception of precipitation, the effect of thick old-growth forest litter and organic mulch upon infiltration, and wetlands or depression storage.

Specifically, while the model is quite effective in predicting the magnitude of primary isotopic dampening related to mixing and storage processes, it is not sensitive to fine scale and short-term variations in isotopic behavior produced by second-order mechanisms. However, these second-order effects also support the argument that the unique forest cover of the basin impacts river behavior. For example, there is a slight decrease in both river and precipitation d^{18}O values in early fall (Figure 8), which indicates precipitation water is reaching the rivers more rapidly than spring and summer. The timing of this shift also correlates to the period of leaf shedding at this high-latitude basin. It seems very likely that precipitation water would reach rivers more rapidly following the shedding of leaves, thereby reducing the volumetrically significant interception and leaf storage of the dense forest.

Water chemistry may also hint at the significant role that old-growth forest may play on regulating river systems. The typical pH of the Wolf and Red Rivers range from 7.4 to 7.9 (Olcott, 1968; Menominee County Environmental Office, file data), which seems low for rivers that appear to be dominated by calcite-dolomite saturation. This suggests that organic acids from decaying vegetation in the forest may play an important role in regulation of the river water chemistry.

It was also observed that the magnitude of variation in discharge, oxygen isotope values, and specific conductance on the Wolf and Red Rivers is much smaller than for disturbed yet similar size rivers in the Midwestern USA. The degree of surface modification, especially with respect to original vegetation type, appears to strongly influence groundwater-surface water interaction and is a topic that should be further investigated in other basins with different degrees of original vegetation cover disturbance. The dominance of undisturbed lands within the study area suggest that unmodified river basins have reached an equilibrium state with regard to these parameters, and that modification to natural forest and wetland systems may produce dramatic variations in discharge rate and water chemistry. As much of the Midwestern USA was originally a mature climax forest, the modern observation of most river basin response may capture a historical "snapshot" of a metastable but geologically inaccurate portrait of real basin behavior.

CONCLUSIONS

Variations of flow, electrical conductance, and d^{18}O values are small for the Wolf and Red Rivers, Wisconsin, a consequence of the large natural storage of this relatively undisturbed watershed. The d^{18}O values indicate that stream flow is a damped running average of local meteoric precipitation that has been homogenized in shallow groundwater reservoirs for 0.34 to 1.1 years. These residence times are long for small midwestern USA rivers (<1000 cfs) and likely reflect the high proportion of old growth forest within the watershed. Deviations from the damped average model are caused by melting of accumulated snow during springtime. Small decreases in the ^{18}O content of precipitation and of streamflow accompany increase in elevation in the basin. The average d^{18}O values of the rivers and the specific conductance of river baseflow are similar to that of shallow groundwaters from nearby wells.

ACKNOWLEDGEMENTS

Special thanks go to EBM's former colleagues at the College of the Menominee Nation, especially Diana Morris, Khaled Boubenider, and Katherine Hall. Several students from the tribal college who deserve acknowledgement for fieldwork assistance include Robin Pitt, John Bobolz, Kathy and January Zernike, Beverly Doxtar, and Terri and Leslie Peters. This research would not have been possible without the support of Larry Waukau of Menominee Tribal Enterprises and Verna Fowler, president of the College of the Menominee Nation. Greg Bunker of the Stockbridge Tribe Environmental Services Department collected some precipitation data. Dave Corn (Menominee Water District) and Ron Jesse (Shawano Water District) provided access to many water wells. Thoughtful and constructive review was provided by Seth Rose at Georgia State University and Timothy Rose (no relation to Seth Rose) at Lawrence Livermore National Laboratory. Supported by NSF grant EAR-0243135 (EBM) and by NSF grant EAR-0106925 (REC).

REFERENCES CITED

Bean, E.F. 1949. Geological map of Wisconsin. Wisconsin Geological and Natural History Survey, 1 sheet.

Berkstresser, C.F., Jr. 1964. Ground water resources of Waupaca County, Wisconsin. US Geological Survey Water Supply Paper 1669-U, 38 pp.

Epstein, S., and T. Mayeda. 1953. Variation of ^{18}O content of waters from natural sources. Geochimica Cosmochimica Acta 4, 213-224.

Frederickson, G.C., and R.E. Criss. 1999. Isotope hydrology and residence times of the unimpounded Meramec River Basin, Missouri. Chemical Geology 157, 303-317.

Fritz, P., D.J. Cherry, K.U. Weyer, and M.G. Sklash. 1976. Runoff analyses using environmental isotope and major ions. *in*: Interpretation of environmental isotope and hydrochemical data in groundwater hydrology. International Atomic Energy Agency, Vienna, 111-130.

Harder, H.A., and W.J. Drescher. 1954. Ground water conditions in southwestern Langlade County, Wisconsin. US Geological Survey Water Supply Paper 1294, 39 pp.

Hendershot, W.H., S. Savoie, and F. Courchesne. 1992. Simulation of stream-water chemistry with soil solution and ground water flow contributions. Journal of Hydrology 136, 237-252.

Hooper, R.P., and C.A. Shoemaker. 1986. A comparison of chemical and isotopic hydrograph separation. Water Resource Research 22, 1444-1454.

Menominee County Environmental Department. 2000. Open File Data

Mook, W.G., D.J. Groeneveld, A.E. Bouwn, and A.J. Gansurjk. 1974, Analysis of a run-off hydrograph by means of natural 18O. *in*: Proceedings symposium on isotope techniques in groundwater hydrology, International Atomic Energy Agency, Vienna, 145-153.

National Oceanic and Atmospheric Administration. 2000. Open File Data for Wisconsin Climate. Complete database available at http://www.crh.noaa.gov/grb/data/index.htm

Olcott, P.G. 1968. Water resources of Wisconsin: Fox-Wolf River Basin. US Geological Survey Hydrologic Investigations Atlas HA-321, 2 sheets.

Pearce, A.J., M.K. Stewart, and M.G. Sklash. 1986. Storm runoff generation in humid headwater catchments 1. Where does the water come from?. Water Resource Research 22, 1263-1272.

Peters, D.L., J.M. Buttle, C.H. Taylor, and B.D. LaZerte. 1995. Runoff production in a forested, shallow soil, Canadian shield basin. Water Resources Research 31, 1291-1304.

Pilgram, D.H., D.D. Huff, T.D. Steele. 1979. Use of specific conductance and contact time relations for separating flow components. Water Resource Research 15, 329-339.

Pinder, G.F., J.F. Jones. 1969. Determination of the ground water component of peak discharge from the chemistry of total runoff. Water Resource Research 5, 438-445.

Rose, S. 1996. Temporal environmental isotopic variation within the Falling Creek (Georgia) watershed: Implications for contributions to stream flow. Journal of Hydrology 174, 243-261.

Rose, T.P., M.L. Davisson, R.E. Criss, and D.K. Smith. 1999. Isotopic investigation of recharge to a regional groundwater flow system, Great Basin, Nevada, USA. Proceedings of the International Symposium on Isotope Techniques in Water Resource Development and Management, Vienna, 10-14 May 1999, International Atomic Energy Agency IAEA-CSP-2/c, 63-72.

Shafer, M.M., J.T. Overdier, J.P. Hurley, D. Armstrong, and D. Webb. 1997. The influence of dissolved organic carbon, suspended particulates, and hydrology on the concentration, partitioning and variability of trace metals in two contrasting Wisconsin watersheds. Chemical Geology 136, 71-97.

Shawano Water District. 2000. Open File Data. Shawano Water District offices, Shawano, WI.

Sklash, M.G., R.N. Farvolden, and P. Fritz. 1976. A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer. Canadian Journal of Earth Science 13, 271-283.

Sklash, M.G., and R.N. Farvolden. 1979. The role of groundwater in storm runoff. Journal of Hydrology 43, 45-65.

USGS. 2000. Open File Data for Wisconsin Rivers. Complete database available at http://water.usgs.gov/wi/nwis/

Van Schmus, W.R., B.A. Brown, and M.G. Mudry. 1998. International Field Conference: Proterozoic Granite Systems of the Penokean Terrane in Wisconsin. Wisconsin Geological and Natural History Survey Open File Report 1998-10, 184 pp.

Waite, P.J. 1960. Climates of the states, Wisconsin. US Weather Bureau, no.60-47, 16 pp.

Wallis, P.M. 1979. Sources, transportation, and utilization of dissolved organic matter in groundwater and streams. Inland Waters Directorate, Ottawa, Ontario, Science Series no.100, 49 pp.

Winston, W.E., and R.E. Criss. 2002. Geochemical variations during flash flooding, Meramec River basin, May 2000. Journal of Hydrology 265, 149-163.

Erik Melchiorre
Associate Professor of Geology
Dept. Geological Sciences
California State University
5500 University Parkway, BI-116
San Bernardino, CA 92407

Email: emelch@csusb.edu