Stream water bypass through a meander neck, laterally extending the hyporheic zone

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Abstract A meander lobe neck diverts stream water into a hyporheic flow path adjacent to a low gradient stream, Little Kickapoo Creek, Illinois, USA. Hyporheic processes have been well-documented in surface water–groundwater mixing zones underlying and directly adjacent to streams. Alluvial aquifers underlying meander necks provide a further extension of the hyporheic zone. Hydraulic head and temperature data, collected from a set of wells across a meander neck, show stream water moves through the meander neck. The hydraulic gradient across the meander neck (0.006) is greater than the stream gradient (0.003) between the same points, driving the bypass. Rapid subsurface response to elevated stream stage shows a hydraulic connection between the stream and the alluvial aquifer. Temperature data and a Peclet number (Pe) of 43.1 indicate that thermal transport is dominated by advection from the upstream side to the downstream side of the meander neck. The temperature observed within the alluvial aquifer correlates with seasonal temperature variation. Together, the pressure and temperature data indicate that water moves across the meander neck. The inflow of stream water through the meander neck suggests that the meander system may host biogeochemical hyporheic zone processes.

Résumé Le lobe d'un méandre abandonné dérive l'eau d'une rivière vers la zone d'écoulement hyporhéique, adjacent à un cours d'eau à faible gradient, dans le bassin de Little Kickapoo, Illinois, USA. Le processus hyporhéique a été bien documenté en tant que zones de mélange, sous le cours d'eau et directement adjacent à ce dernier. Les aquifères alluviaux situés sous le méandre abandonné, représentent une extension éloignée de la zone hyporhéique. Les données piézométriques ainsi que les données de température, collectées dans différents puits situés à travers le méandre en question, montrent que l'eau souterraine s'écoule à travers ce dernier. Le gradient hydraulique à travers le méandre (0.006) est plus important que le gradient de la rivière voisine (0.003) mesuré entre les mêmes points. La réponse rapide de la sub-surface, lors des fluctuations du niveau du cours d'eau, montre qu'il existe une connection entre ce dernier et l'aquifère alluvial. Les données de température et le nombre de Péclet (43.1) indiquent que le transport thermique est dominé par le mouvement d'advection de l'amont vers l'aval du méandre étudié. La température levée dans l'aquifère alluvial a été corrélée avec les variations saisonnières de la température. Ensemble, la pression et la température indiquent que l'eau traverse le méandre. L'écoulement à travers le cours d'eau vers le méandre, suggère que le système du méandre pourrait abriter des processus biogéochimiques propres aux zones hyporhéiques.

Resumen Un lóbulo de cuello de meandro desvía agua de río hacia una ruta de flujo hiporreica adyacente a un arroyo de gradiente bajo en el Arroyo Pequeño Kickapoo, Illinois, USA. Se han documentado bastante bien procesos hiporreicos en zonas de mezcla de agua subterránea con agua superficial las cuales subyacen y son adyacentes a los ríos. Los acuíferos aluviales que subyacen cuellos de meandros aportan extensión adicional de la zona hiporreica. Los datos de temperatura y presión hidráulica que se colectaron en un grupo de pozos a través del cuello de meandro muestran que el agua del río se mueve a través del cuello de meandro. El gradiente hidráulico a través del cuello de meandro (0.006) es mayor que el gradiente fluvial (0.003) entre los mismos puntos que conducen el desvío. La respuesta subsuperficial rápida al nivel elevado del río muestra una conexión hidráulica entre el río y el acuífero aluvial. Los datos de temperatura y el número de Peclet (Pe) de 43.1 indican que el transporte termal es dominado por advección desde la parte alta del río hasta la parte baja del cuello de meandro. La temperatura observada dentro del acuífero aluvial correlaciona con la variación estacional de la temperatura. De manera conjunta, los datos de presión y temperatura indican que el agua se mueve a través del cuello de meandro. La entrada de agua de río a través del cuello de meandro sugiere que

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el sistema de meandro puede alojar una zona hiporreica de procesos biogeoquímicos.

Keywords Groundwater/surface water relations · Temperature · Hyporheic zone

Introduction

Conceptually, streams are systems of pathways interacting along four dimensions: three spatial dimensions, longitudinal, lateral, and vertical; and time (Ward 1989). The longitudinal dimension serves as the theoretical basis for ecological models such as the river continuum concept (Vannote et al. 1980) and the nutrient spiraling concept (Elwood et al. 1983) and includes linkages between the upstream and downstream biotic and abiotic variables. The active channel and adjacent riparian and floodplain systems exchange organisms, thermal energy, organic matter, and nutrients along the lateral dimension (Creuze des Chatelliers et al. 1994). Similar geochemical, hydrological, and biological transfers and transformations occur along the vertical dimension with the interaction and mixing of stream and subsurface water (Bencala 2000; Brunke and Gosner 1997; Stanford and Ward 1988).

Understanding the interactions that create the hyporheic zone requires knowledge of groundwater flow paths and their linkages to streams, rates of exchange between stream and groundwater systems, and the mechanisms that generate spatial (channel unit, reach, and watershed) and temporal (diurnal, seasonal, and interannual) variations in these processes (Boulton et al. 1998; Dahm and Valett 1996; Wroblicky et al. 1998). Recent work has begun to address Hynes' (1983) call for integrating hydrogeology and ecology, which he argued was needed to delineate the hyporheic zone and to synthesize a comprehension of the structure and function of riverine and hyporheic ecosystems. However, research into the physical factors that control the interaction between surface water and groundwater has focused primarily on either high-energy streams (e.g., Bencala et al. 1984; Bencala and Walters 1983; Kasahara and Wondzell 2003) or laboratory experiments and numerical simulations (e.g., Packman and Bencala 2000; Wroblicky et al. 1998). Consequently, a significant gap exists between the relatively detailed physical understanding of driving forces that cause surface–subsurface exchange in the laboratory and what is observed in the field (Harvey and Wagner 2000) for many geological/hydrogeological settings.

As two of the most important physical factors in stream function and structure (Allan 1995), fluid potential and thermal energy provide a way of monitoring and delineating the surface water–groundwater interaction. These variables can dictate the distribution, success, and diversity of species, populations, and communities in streams. Fluid potential controls the exchange between the surface water and the groundwater. Temperature is directly related to the interchange of surface water and groundwater and regulates primary production, respiration, metabolism, reproduction, and growth rate of an organism (Bott 1983; Sweeney and Vannote 1981; Vannote and Sweeney 1980). The hyporheic zone may provide a refuge from thermal fluctuations induced by seasonal changes, frontal passages, diurnal variations and anthropogenic impacts (Brunke and Gosner 1997; Dole-Olivier and Marmonier 1992; Dole-Olivier et al. 1997; Grimm et al. 1991; Stanford and Ward 1993; Williams 1984).

Examination of fluid potential (head) and thermal variations within the surface and alluvial water is one way to measure the degree of interaction between the stream and the alluvial aquifer (Conant 2004; Dogwiler 2002; Fraser and Williams 1998; Stewart et al. 1998; White et al. 1987). Temperature patterns have been effectively used to identify the extent of the hyporheic zone (White et al. 1987) and to delineate surface water–groundwater mixing zones, where the temperature in the zone is controlled by advection of groundwater, advection of stream water, or conduction from the surface (Silliman and Booth 1993). Temperature has also been used to track surface water infiltration and fluid flux in hyporheic sediments (Constantz et al. 2003; Harvey et al. 1996; Ronan et al. 1998).

The majority of published hyporheic zone research has focused on stream systems in high-gradient, high-energy, coarse-sediment mountain streams (e.g., Jones and Mulholland 2000). This invaluable work has established a foundation for understanding hyporheic processes, but while the fundamental principles remain, different factors may dominate in other hydrogeological systems. Low-gradient streams with finer sediments are common throughout much of the United States, but have received far less attention. These systems develop floodplains and meanders that are qualitatively distinct—hydrogeologically, geochemically, and biologically—from the alpine and subalpine streams that have so far been well studied. Within a floodplain, Grannemann and Sharp (1979) identified four types of groundwater response to changes in river stage. In addition, their simulations identified a potential for surface water to travel through a meander neck, bypassing the stream channel, similar to Kasahara and Wondzell's (2003) split-channel and secondary channel diversions. Longer residence times in a low-gradient system, however, provide more opportunity for the hyporheic water to chemically evolve and for the local biota to establish different and distinct communities. An interaction of surface water and groundwater within the meander neck, an extension of Ward's (1989) lateral dimension to the subsurface alluvial aquifer, would suggest that transfer within the hyporheic zone of biota, solute, and organic matter may extend to an entire meander lobe system. Numerical simulations predict this type of behavior (Grannemann and Sharp 1979; Wroblicky et al. 1998), and work in high gradient streams illustrates the interaction (Kasahara and Wondzell 2003; Wondzell and Swanson 1999; Wroblicky et al. 1998). However, verification from field observations of low-gradient streams with fine-grained sediment has not been reported. Using water temperature and head data obtained

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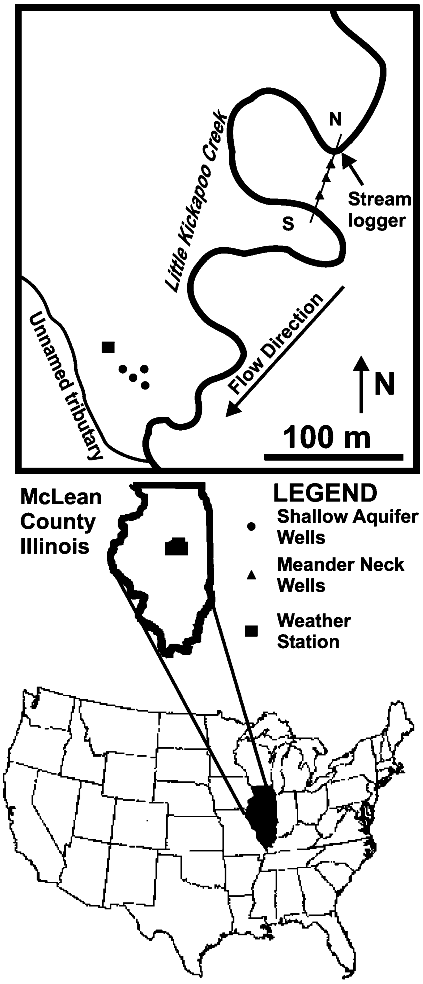

Fig. 1 Site map for the study reach on Little Kickapoo Creek (Illinois), flowing northeast to southwest. Map also identifies the placement of the wells across the meander neck

from wells across a meander neck in a low-gradient, third-order stream with silty–clayey sandy banks and floodplain, this work tests the hypothesis that stream water will bypass a stream channel and move through a meander neck.

Modifying the analysis of Silliman and Booth (1993) on the effects of stream temperature on the sediment temperature in various stream settings, three hypotheses may explain observed variation in the temperature in a meander neck: (1) the change in temperature is driven by vertical conduction from the meander lobe surface and is a result of the seasonal temperature pattern, indicating little to no flux of stream water through the meander neck; (2) the change in temperature is driven by advection of stream water through the meander neck, and thus would indicate a flux of stream water through the sediment; or (3) the change in temperature is driven by advection of stream water combined with groundwater flow. Any of these hypotheses could be appropriate. If the temperature observed in the aquifer were strictly controlled by conduction from the surface, there should be a uniform change in temperature across the meander neck. If temperature were controlled by stream water advection, there should be a progressively muted temperature front as stream water equilibrates with the sediment as the water flows through the neck. If temperature were controlled by surface water–groundwater mixing, the signature could be indistinguishable from advection alone.

Site description

Little Kickapoo Creek is a third-order perennial stream originating in urban area, about 11 km north of the study site, which is located in rural McLean County, Illinois, USA (Fig. 1). The climate of central Illinois is humid continental with cold winters and warm summers. During the period from 1950 to 2002, the annual mean temperature was 11.2 °C and the annual mean precipitation was 93 cm, which was distributed rather evenly throughout the year.

The drainage area upstream from the study site is about 52 km^2. Upstream from the study site, the stream has been straightened to a sinuosity index (SI) of 1.1. Locally, the stream is unmodified (SI of 1.8), relatively unobstructed, and meanders through an alluvial valley bisecting end moraines in a Wisconsonian glacial plain. Within the valley, groundwater flow is from the north–northeast to the south–southwest and is represented by the baseflow end member described by Larkin and Sharp (1992).

This study focuses specifically on an alluvial aquifer located across the neck of a meander lobe of Little Kickapoo Creek (Fig. 1). The term “aquifer” is loosely applied here since the underlying hypothesis argues that the meander neck is an atypical hyporheic flow path. The meander is 67 m from the neck to the point bar, 71 m at the widest point, and the neck is 31 m across. The surface of the meander lobe is highly vegetated with deciduous trees and scrubby brush. The upper 2 m of the meander lobe consists of muddy alluvial flood plain deposits (Cahokia Alluvium), which acts as an aquitard when water levels rise above its base. The alluvium is olive-gray to olive-green for the top ~1.8 m, suggesting reducing conditions, but is increasingly mottled orange for the bottom ~0.2 m, suggesting oxidizing conditions at its base. Below the alluvium, is a layer of sand and gravel (Fig. 2), which is either the top of the Henry Formation, a glacial outwash deposit, or the relict streambed composed of reworked Henry Formation material. The transition from muddy sands to the sandy gravel begins at an elevation of 228.1 m a.s.l., slightly higher than the present elevation of the streambed, 227.5 m a.s.l. Locally, the Henry Formation is about 6 m thick, below which the Wedron Group lodgement till, being dominated by low-permeability clay, serves as a lower confining unit. The streambed runs just below the top of the sandy gravel unit and is bounded by sharply incised banks cut into alluvium and low relief depositional point bars. The channel substrate is primarily gravel and coarse sand with minor interstitial silt. The local scale geology reflects the geology of the stream valley.

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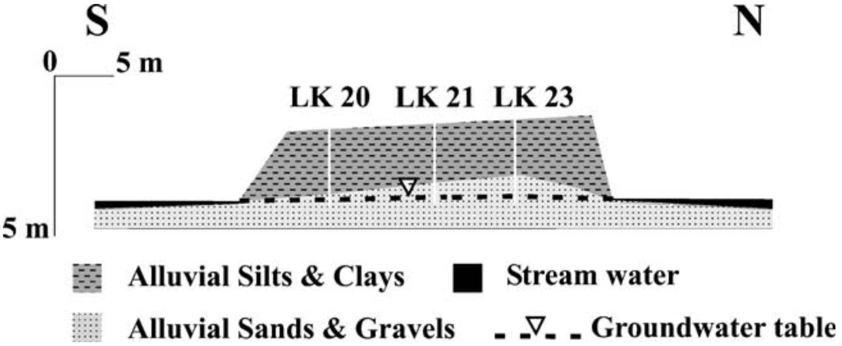

Fig. 2 A cross section of the meander identified in Fig. 1, showing the location of observation wells LK 20, LK 21, and LK 23. The cross section also shows the transition from the silt–clay layer to the sand–gravel unit, and the position of the sand-gravel unit to the streambed. Note that vertical exaggeration is 2×

Little Kickapoo Creek is regionally a gaining stream. Groundwater maintains a typical baseflow of about 0.1 m^3/s during extended dry periods; runoff, interflow, tributaries, and field drain tiles contribute during higher stages following precipitation. Peak recorded flow (between April 2003 and January 2005) was greater than 4 m^3/s at a mean velocity of 0.25 m/s (peak measured velocity 1.2 m/s) and a maximum depth of ~1.3 m. Regionally, the gradient of the stream is about 0.002. Around the meander, the stream channel has a number of riffles, runs, and pools that produce a local gradient 0.003. The point-to-point stream gradient across the meander neck from N to S (Fig. 2) at baseflow is 0.006±0.0005 (n=5).

Methods and materials

In the spring of 2003, three vented observation wells (LK 20, LK 21, and LK 23) were emplaced across the meander neck to a depth of 2.5 m (Fig. 2). Detailed surveying of the meander lobe and wells provided the elevation of the well screen and the position of the individual wells. The screened interval for all wells, 228.2 to 227.5 m a.s.l., coincides with the gravelly-sand zone that is at the same elevation as baseflow within the stream. Hydraulic conductivity of the aquifer (geometric mean=9.3 m/day, n=12,), derived from slug tests performed on the three wells, and grain-size analysis (method described by Alyamani and Sen 1993; n=9, geometric mean=13.2 m/day) of the sediment cores, is on the order of 10 m/day (~0.01 cm/s). Variations in estimates of hydraulic conductivity as a function of temperature-dependent viscosity and density do not greatly extend the range of the estimate; the hydraulic conductivity of 10 m/day used here remains a reasonable value. Solinst Leveloggers capable of recording pressure head (resolution: 0.002 m) and temperature (resolution: 0.01 °C) were installed within the screened interval in each well, and a Solinst Barologger was installed at the land surface to allow for barometric compensation and to record air temperature. The loggers recorded measurements every 15 min from April 2003 to November 2004. For each well, the pressure head data, compensated for barometric pressure, were combined with the elevation head (survey data) to provide a total head value. Additionally, a multi-parameter logger that recorded temperature (resolution: 0.01 °C) and water depth (resolution: 0.001 m; Fig. 1) was installed in the stream. Due to technical problems, stream stage data were limited from May to August 2003, and the stream temperature data were collected from May 2003 to January 2004 and from September to October 2004.

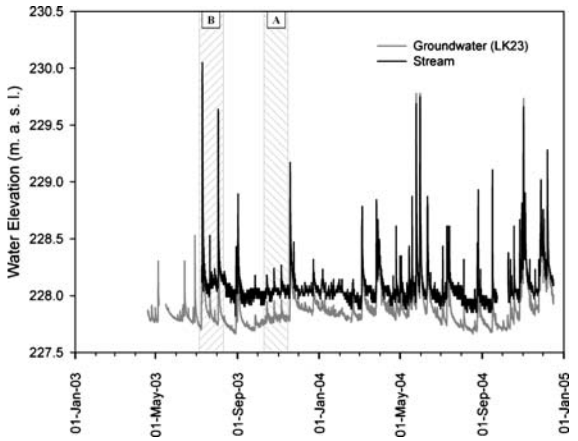

Fig. 3 Observed stream elevation and groundwater elevation for observation well LK 23. LK 20 and LK 21 were not included because at the current scaling the lines for LK 20, LK 21, and LK 23 overlay each other. However, the trends for LK 20 and LK 21 are similar to LK 23. The *hatched areas* (**a**) and (**b**) represent the scales of Figs. 4 and 5, respectively

Results and discussion

Pressure

Field monitoring of stream stage and hydraulic head values within the alluvial aquifer indicate a strong link between the two systems. The data show that the hydraulic head in the alluvial aquifer tracks the stage of Little Kickapoo Creek (Figs. 3, 4, 5). Depending upon the flow regime (high flow vs. baseflow), the influence of stream stage on the alluvial aquifer varied. While Little Kickapoo Creek is generally a gaining stream, the data

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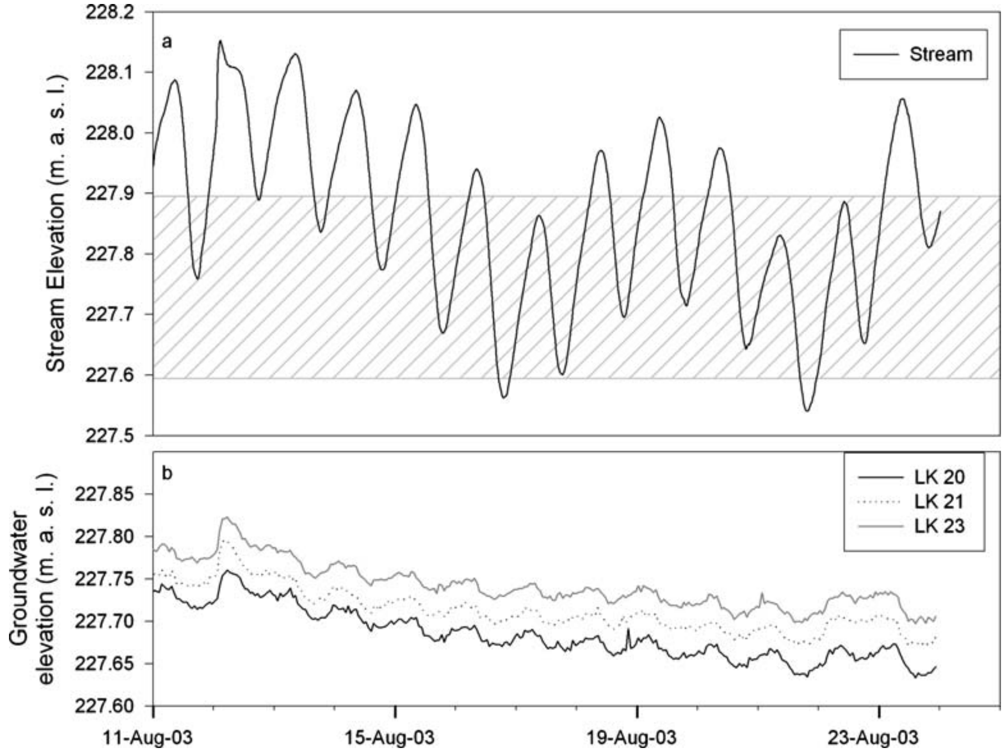

Fig. 4 Higher resolution **a** stream and **b**)groundwater (LK 20, LK 21, LK 23) elevation data for a period of baseflow in August 2003. The period is highlighted as *hatched area* (*A*) in Fig. 3. The *hatched area* in the *stream graph* (**a**) represents the elevation scale used in the *groundwater graph* (**b**)

illustrate (Fig. 3) that locally the meander neck pirates stream water.

Across the neck, LK 23, on the upstream side, generally exhibited the highest hydraulic head, and LK 20 the lowest hydraulic head. This was consistent during baseflow conditions. Using the hydraulic head data within the wells, the head gradient is 0.006 across the meander neck. The gradient as measured in the wells is similar to the straight-line stream gradient measured directly across the meander neck, 0.006. Both gradients are higher than the longitudinal channel gradient for the stream, 0.003, indicating a potential for stream water diversion through the meander neck. Using the gradient of 0.006 and the hydraulic conductivity of 10 m/day, specific discharge across the meander would be 6.0×10^{-2} m/day (7×10^{-5} cm/s).

During baseflow conditions of mid-August, 2003 (Fig. 4), stream stage and the groundwater head follow the same general trend, but with the sharply pronounced diurnal variations in stream stage appearing very subdued in the aquifer. The peaks occur at about sunrise, and the nadirs occur late in the afternoon: presumably, upstream groundwater discharge to the stream is greatly reduced by evapotranspiration. The aquifer shows a pattern similar to that found by Lewis et al. (2002), and suggests that diurnal variations within an alluvial aquifer are associated with the stream. The aquifer tracks stream stage following

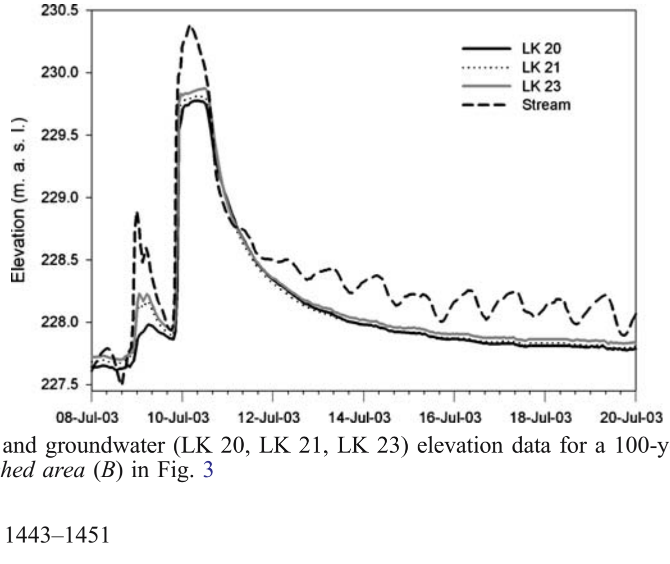

Fig. 5 Higher resolution stream and groundwater (LK 20, LK 21, LK 23) elevation data for a 100-year storm event in July 2003. The storm event is highlighted as *hatched area* (*B*) in Fig. 3

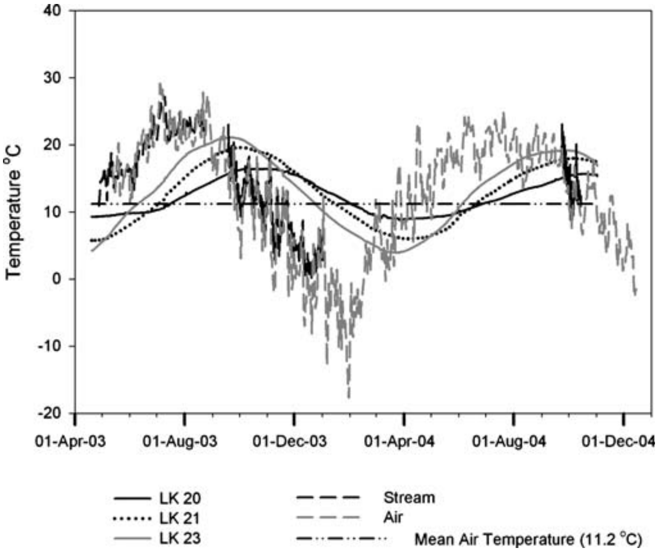

Fig. 6 Observed daily average stream temperature, aquifer temperature (LK 20, LK 21, and LK 23), air temperatures, and annual mean air temperature (11.2 °C). According to Domenico and Schwartz (1990) the annual mean air temperature ±1 to 3° C is representative of the groundwater temperature

precipitation within the 15-min measurement period, with a magnitude that more closely matches the stream than the aquifer response to diurnal fluctuations (Figs. 4, 5, 6). Regardless of the magnitude of variations in stream stage and aquifer water table elevation, the gradient between the wells (Fig. 4) does not change significantly. The total head response within the aquifer implies that the aquifer provides short-term bank storage by compressing the water beneath the confining Cahokia Alluvium, and the constant gradient suggests that the gradient within the aquifer is controlled by the stream.

During rising stages following precipitation, head within the alluvial aquifer quickly responds to stream stage, and stream and aquifer peaks coincide within the 15-min time resolution of the data (Fig. 5). On July 9 and 10, 2003, the Little Kickapoo Creek watershed experienced a 100-year precipitation event, receiving 20.85 cm of rain in less than 48 h. The response in the stream and in the alluvial aquifer was typical of other storm events, but amplified (Fig. 5). During the 100-year event, Little Kickapoo Creek flooded the meander lobe and adjacent stream valley. Response within the aquifer was rapid: from the stream to the most downstream well (LK 20), the water elevation rose within a 15-min window. The short lag time implies a high degree of connection between the alluvial aquifer and the stream. The highest peak amplitude was recorded in the most upstream well (LK 23), with lower peak amplitudes observed in the downstream wells (LK21 and LK 20). After 10 days, the normal baseflow gradient returned with LK 20 having the lowest water elevation.

Numerical simulations have shown that meander curvature promotes hyporheic flow through point bars (Cardenas et al. 2004; Matos et al. 2003). The head data illustrate this phenomenon and confirm that the meander pirates surface water as a hyporheic flow through the meander neck. The results are consistent with the by-pass described in high-gradient, high-energy streams (Kasahara and Wondzell 2003; Wondzell and Swanson 1999; Wroblicky et al. 1998) and extend the concept of hyporheic bypassing through a meander neck to low-gradient, low-energy systems.

Temperature

Aquifer water temperature and air temperature data were collected during the entire study period. However, due to technical problems, the stream temperature was monitored only from May 2003 to January 2004, and again from September 2004 to October 2004. During the period when both stream and air temperature were being monitored, the two showed a strong correlation (r=0.947; Fig. 6). Stream water temperature is most influenced by air–water interaction (Fraser and Williams 1998; Mohseni et al. 1998; Sinokrot and Stefan 1993). Since stream temperature was not monitored over the entire duration of the study, and given the strong correlation with the air temperature when both were recorded, the air temperature was used as a proxy for the missing stream water temperature data.

Air and stream water temperatures varied diurnally as a function of the amount of solar radiation, with the highest temperatures occurring in mid-afternoon (4:00 PM) and the lowest temperatures occurring in the morning (6:00 AM). If the diurnal cycle is removed by calculating an average daily temperature, the resulting trend closely followed the average annual temperature signature (Fig. 6). As expected, both the air and stream show a seasonal cycle, with high temperatures in the summer and low temperatures in the winter. Note that the average spring–summer 2003 temperatures were 1.5 °C warmer than the temperatures for the same period in 2004.

On a time-scale of a day, conditions within the aquifer are much different than within the stream. No diurnal temperature variation was observed; rather, water temperature gradually increased beginning in late spring and continued to increase into late summer–early fall, when the temperatures began to decrease (Fig. 6) following the seasonal variation in the stream water temperature. The temperature signatures for the individual wells indicate that the rates of temperature change decrease down-gradient across the meander neck. Separately, each well's rate of increase in temperature (spring to fall) was identical to its own rate of decrease (fall to spring) in temperature. Calculated rates were 0.045, 0.08, and 0.10 °C/day for LK 20, LK 21, and LK 23, respectively. Additionally, the temperatures observed in LK 23, LK 21, LK 20 correlate to the stream water temperature with lags of 67 days (r=0.875), 78 days (r=0.930), and 107 days (r=0.932), respectively. The temperatures recorded in LK 23 correlates to those recorded in LK 21 (r=0.985) and LK 20 (r=0.986) with lag times of 11 and 30 days, respectively. The 2004 peak temperature dates in all three wells were within five days of the 2003 peak temperature dates. The 2004 peak aquifer temperatures were 1.5° C cooler than in 2003, further confirming a climatic control on the temperature of the groundwater.

As water flows into sediment of a different temperature, the two masses will exchange heat to equilibrate. If vertical heat conduction from the surface dominated the local heat equilibration, temperatures would change nearly uniformly in the three wells, assuming equal incident radiation. Uniform temperature change is not observed; rather there is an uneven heat exchange occurring. Shading differences may cause the uneven heat exchange. A thick canopy of deciduous trees completely shades wells LK21 and LK23 during the summer; LK20 is partially shaded. Given unequal incident radiation, if conduction from the surface dominated the system, LK20 would show the fastest and greatest increase in temperature, contrary to observations. Hence, the effect of shading is not significant. The non-uniform temperatures and rates of temperature change show that vertical conduction does not control temperatures within the aquifer, thus eliminating the first hypothesis stated in the introduction.

If lateral heat conduction from the banks dominated, the two outer wells (LK20 and LK23) would show patterns similar to each other, with the middle well (LK21) lagging and with a subdued response, again contrary to observations. The magnitude and rates of change, and the increasing lag times down-gradient strongly support the hypothesis that stream water flows through the meander neck from the up stream to the downstream side. Using the specific discharge (q) of 6.0×10^{-2} m/day, a characteristic length (L) of 31 m (length of flowpath through the meander neck), a water density (ρ_w) of 1,000 kg/m^3, the specific heat of water (C_w) of 1.0 kcal^{-1} kg^{-1} °C^{-1}, and a thermal conductivity (λ) of 43.2 kcal days^{-1} m^{-1} °C^{-1} (a value representative of the sediment provided by Lapham 1989), a Peclet number (Pe) of 43.1 was calculated using the equation $P_e = \frac{qL\rho_w C_w}{\lambda}$ (Domenico and Schwartz 1990). The Pe of 43.1 indicates that advective heat transport dominates over lateral conductive heat transport. Thus, one can eliminate the hypothesis that alluvial aquifer water temperatures are controlled by lateral conduction.

The stream influences the temperature within the aquifer: temperature in the aquifer follows the seasonal trend in the stream, and the rate of change decreases across the meander neck as the flowing water partially equilibrates with the substrate. The most extreme temperature variation was noted in LK 23, which is the furthest upstream well (21.1–3.8 °C), and the most stable temperature was in LK 20 (16.4–8.75 °C), the most downstream well. The range of temperatures recorded in LK 20 indicates the water in LK 20 is not just groundwater, since the groundwater would have a temperature of 11.2±3 °C—the average annual temperature plus or minus the range described by Domenico and Schwartz (1990).

Groundwater surface water mixing may contribute to the variations in temperature and rate of thermal exchange. The temperature at a specific point in the aquifer would then depend on the proportions and temperatures of the two source waters. Based on this concept, temperature could be used as a method of estimating which water source dominates at a discrete point in the hyporheic zone. For example, areas where the subsurface temperature is closer to stream water than groundwater temperature would suggest that the aquifer water is composed primarily of stream water and is a potential area of recharge or parallel flow.

Another possible explanation for the various rate of temperature change is that the flux of groundwater moving into the meander neck is variable in both space and time. Using the specific discharge of 6.0×10^{-2} m/day would provide a lag time of 105 days between the stream and LK 23 compared to the observed lag time of 67 days. Between LK 23 and LK 21, advection alone would produce a lag time of 90 days instead of the observed 11 days. Since the variation in temperatures in LK 23 cannot be explained solely by variations observed in the stream temperature (r=0.875), upwelling or lateral groundwater may contribute to the thermal balance of the system. No data are available about the vertical or lateral gradient across the meander neck for the period of this study. This hypothesis remains viable, and may be supported by the diurnal head response in the aquifer that is subdued relative to the stream. This possibility requires further study.

Dogwiler (2002) argued that during times of high hydrologic input into a system, large volumes of thermally unequilibrated water overcome the thermal buffering capacity of the stream substrates and leads to increased homogenization of temperatures vertically and longitudinally in the stream and sediment. Essentially, the storm-induced thermal pulses enter the substrate with little to no thermal loss, which can create a thermal disturbance within the hyporheic ecotone. In contrast to Dogwiler's stream substrate, the hyporheic zone within a meander neck appears to behave in a much more stable manner. The stage on the up- and down-stream sides of the neck correlate almost perfectly and instantaneously with each other and with the head within the aquifer within the time resolution of this study; hence, the gradient is maintained. The specific discharge and, thus, the rate of advection remain constant through the neck. For instance, the 100-year precipitation event of July 9–10, 2003 resulted in no measurable increase in temperature, although the hydrograph (Fig. 5) suggests a significant volume of bank storage within the watershed.

Building upon the analysis of Silliman and Booth (1993) on the effects of stream temperature on the sediment temperature in various stream settings, three hypotheses may explain variation in the temperature in the meander neck: (1) the change in temperature is driven by conduction from the meander lobe surface and is a result of the seasonal temperature pattern, indicating little to no flux of stream water through the meander neck; (2) the change in temperature is driven by advection of stream water through the meander neck, and thus would indicate a flux of stream water through the sediment; or (3) the change in temperature is driven advection of stream water combined with groundwater flow. Any of these hypotheses could be appropriate. However, if the temperature observed in the aquifer was strictly controlled by conduction from the surface, there should be a uniform change in temperature across the meander neck. The recorded temperatures show that the rate of change varies with the position on the meander neck, with the up-gradient temperature increasing (or decreasing) at a greater rate and magnitude than the down-gradient wells. Secondly, the cross-correlation results indicate that the temperatures recorded at LK 21 and LK 20 correlate to the temperature recorded days earlier at LK 23, signifying advection across the meander neck. Finally, the delay in the temperature front propagating across the meander shows that the meander neck does not warm (or cool) uniformly across the wells. These observations strongly suggest that the temperature in the meander neck is not driven by vertical conduction but rather is dominated by advection of thermal energy via water flow. Surface water–groundwater mixing could produce a signature indistinguishable from advection only; future work collecting three-dimensional head, temperature, and chemistry data would be required to resolve the relative contributions.

There is a consensus that one of the biological advantages to living in the hyporheic zone is refuge from thermal fluctuations in a stream induced by seasonal changes, frontal passages, diurnal variation, or anthropogenic impacts (Brunke and Gosner 1997; Dole-Olivier and Marmonier 1992; Dole-Olivier et al. 1997; Grimm et al. 1991; Stanford and Ward 1993; Williams 1984). The temperature data show that across the meander neck (and possibly the entire lobe) the temperature varies cyclically, but slowly and moderately. Within the scale of this study, the meander may serve as a refuge; however, an extrapolation to larger systems should not be made without further investigation. In larger systems such as the Missouri River, the influence of groundwater on the within meander lobes may be greater than the bypass of surface water (Grannemann and Sharp 1979).

Conclusions

The data support the hypothesis that stream water bypasses the stream and flows through a meander neck in a low gradient stream. An amplified gradient across the meander neck (versus the stream gradient) drives the flow, consistent with and extending the findings of Cardenas et al. (2004) and Matos et al. (2003). A hydraulic connection is illustrated by the rapid response in pressure recorded within the meander lobe aquifer during high-flow events. The temperature signature within the aquifer is consistent with advection of stream water and is not consistent with vertical conduction from the surface. The surface water bypasses the stream as the water moves through the meander based upon the subdued thermal signatures in the down-gradient wells and the governing role of advection in thermal transport (Pe=43.1). The inflow of stream water through the meander neck suggests that the meander lobe may host processes observed within hyporheic zones. Additional work to look for and quantify the rate of mixing between groundwater and surface water is warranted.

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