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Discussions

Opposite distribution pattern of streambed hydraulic conductivity in losing and gaining stream reaches

X. H. Chen[1], W. H. Dong[1,2], G. X. Ou[1], Z. W. Wang[1], and C. Liu[1]

[1]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583-0996, USA
[2]Key Laboratory of Groundwater Resources and Environment of China Ministry of Education, Jilin University, Changchun 130021, China

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Correspondence to: X. H. Chen (xchen2@unl.edu)

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Abstract

In gaining streams, groundwater seeps out into streams. In losing streams, stream water moves into groundwater systems. The flow moving through the streambed sediments under these two types of flow conditions are generally in opposite directions (upward vs. downward). The two opposite flow mechanism will affect the pore size and fine particle content of streambeds. It is thus very likely that the opposite flow conditions affect the streambed hydraulic conductivity. However, comparisons of the hydraulic conductivity (K) of streambeds for losing and gaining streams are not well documented. In this study, we examined the K distribution patterns of sediments below the channel surface or stream banks for the Platte River and its tributaries in Nebraska, USA. Two contrast vertical distribution patterns were observed from the test sites. In gaining reaches, hydraulic conductivity of streambed decreases with the depth of the sediment cores. In losing reaches, hydraulic conductivity increases with the depth of the sediment cores. This contrast patterns in the two types of streams were mostly attributed to flow directions during stream water and groundwater exchanges. In losing reaches, downward movement of water brought fine particle into the otherwise coarse sediment matrix, partially silting the pores. For gaining reaches, upward flow winnows fine particles, increasing the pore spacing in the top parts of streambed, leading to higher hydraulic conductivity in shallower parts of streambeds. These flux directions can impact K values to depth of greater than 5 m. At each test sites, in-situ permeameter tests were conducted to measure the K values of the top streambed layer. Statistical analyses indicated that K values from the sites under losing stream condition are significantly different from the K values from the sites under gaining stream condition.

1 Introduction

Stream networks drain land surface runoffs and can receive groundwater baseflow as well. In stream-aquifer interactions, water or solute must pass through streambeds that control the hydrologic connectivity between stream water and groundwater. Streambed hydraulic conductivity is a key parameter in the analysis of stream-aquifer interactions. In areas where streamflow depletion is a water management issue, knowledge of streambed hydraulic conductivity is needed in the development of conjunctive water use plans. When rivers are polluted, migration of pollutants from rivers to the adjacent aquifer systems is a big threat to the quality of the groundwater supply systems and thus to human health. Streambed hydraulic properties control the seepage velocity and thus to the movement of contaminants between rivers and groundwater.

Bank filtration processes is associated with downward flow in streambeds and can concentrate fine particulate matters that clog streambeds (Schubert, 2002). Upwelling flow in streambed on the other hand enlarges sediment pore size and enhance streambed hydraulic conductivity (Song et al., 2007). Laboratory experiments in a 1.5-m diameter cylinder indicated that seepage direction at the water–sediment interface of hyporheic setting affects the magnitude of sediment hydraulic conductivity (K) (Rosenberry and Pitlick, 2009a). When streambed mobility is low, upward flow can enhance the hydraulic conductivity and downward flow reduces hydraulic conductivity. The ratio of K determined during upward flow to K determined during downward flow is greater than 1 and can be as high as 2.4 (Rosenberry and Pitlick, 2009a). Downward seepage pulled fine-grained particles onto or into the bed until they clogged pore spaces and reduced K in the sediment volume at or just below the sediment–water interface (Rosenberry and Pitlick, 2009a). Upward seepage velocity at the points of preferential discharge often was sufficient to suspend particles, even with no surface-water current. The upward force thus expands the pore space, leading to higher hydraulic conductivity.

Some lab flume studies (Packman et al., 2000a,b) demonstrated that the forming of clogging layers is a common sedimentation process in streams. Clogging is a very effective process reducing streambed hydraulic conductivity. The simulations using flumes often neglect the groundwater component and do not relate seepage direction to K changes. A recent study by Karwan and Saiers (2012) suggested that clay-sized particles and colloids can travel within the pore space of sediments by stream water filtration in the hyporheic zone. Steady dynamic pressure variations over bed forms induce streamflow to enter streambed and then exit (Elliot and Brooks, 1997). While they did not discuss the possible effect of this filtration on K, it is apparent that when retention of clay takes place in the streambed, the fine materials will likely reduce the hydraulic conductivity. This numerical simulation of particle transport in sediments (Karwan and Saiers, 2012) focuses on the filtration of clay particles in a small scale of sediments (< 0.5 m in depth) below the water–sediment interface. Laboratory studies are conditioned to small sand column or sand box. Thus, these small-scale studies under controlled hydrodynamics conditions did not fully reflect how the streambed hydraulic conductivity has been alternated by upward or downward flow directions in the sediments under natural settings of streambeds. Rosenberry and Pitlick (2009a) suggested that it would be valuable if researchers can document the effects of seepage direction (upward or downward) on the K distribution in the natural world because this directional bias has been neglected in most field investigations. Rosenberry and Pitlick (2009b) confirmed from a field investigation in the South Platte River of Colorado using a seepage meter method that vertical hydraulic conductivity at specific locations varied depending on seepage direction, and was slightly larger to more than an order of magnitude larger during upward seepage than during downward seepage.

Numerical simulations of stream-groundwater interactions across channels indicate that stream water infiltration in streambeds can penetrate a depth greater than one meter and reach a depth of up to 5 m beneath the water–sediment interface (Chen and Chen, 2003). Numerical simulations of hyporheic exchanges along stream longitudinal profiles indicate that stream water penetration into streambeds can reach to a depth up to 10 m (Gooseff et al., 2006). This filtration process, if bringing fine particles into the channel sediments, will thus reduce the pore space of the original framework of the

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streambed, leading to decrease of streambed K in a greater depth than the depth laboratory experiments can illustrate. However, the effective depth of this potential mechanism for reducing K has not been confirmed through field investigation primarily due to the difficulties of measurement of streambed hydraulic conductivities for a larger depth. When water particles travel through the original coarse streambed, more fine particles are likely retained in the top part of streambed and the concentration of suspended fine particles in the flow reduces gradually as the infiltrated stream water plume travels downward. Consequently, this filtration process can form a streambed that have a higher content of silt and clay in the shallow parts of the streambed. It will thus be interesting to investigate how this filtration process affects K variations with depth in losing stream reaches. To the best of our knowledge, careful analysis of K profiles specifically for losing streams has not been conducted.

Opposite to losing streams, gaining streams receive groundwater which migrates predominantly in the vertical direction beneath the water–sediment interface. This upward movement expands pore size and then enhances K of the top parts of streambed (Song et al., 2007; Chen, 2011). Upward flow can pick up fine particles that otherwise are retained to the surface of coarse particles or clog between coarse grains. The water flow in pores suspends the fine particles and brings them upwards into streams; stream currents wash away the fine materials. This winnowing process sorts streambed sediments and leaves coarse materials in streambeds. As a result, the hydraulic conductivity becomes larger in the top layer of streambeds (Dong et al., 2002).

Based on the above analyses, the K distribution in these two groups of streams will be in opposite patterns. It is likely that in losing reaches, streambed K is the smallest near the water–sediment interface and increase with depth; in gaining streams, streambed K is the greatest near the water–sediment interface and decrease with depth. It would be idea that a study is conducted in the same stream reach during a losing condition and a gaining condition, respectively. It is difficult, however, to predict when the change of seepage direction will occur or whether the direction will change for a given stream segment. In this study, we selected several stream reaches which are

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either predominantly under losing condition or mainly under gaining condition. We first determined the losing and gaining conditions at each of the study sites. We then conduct in-channel permeameter tests to determine the K for the top 50-cm streambed. From these K values, we can identify the difference of the K of the top-layer sediments between the two types of streams. We then collect a sequence of cores from sediments below the top layer to a depth about 10 to 15 m and determined K for these cores. From the K profiles with depth, we analyzed the distribution trend of K with depth for these two types of streams.

2 Study area and methods

2.1 Study area

The study area is in the Platte River valley of south-central and eastern Nebraska, USA. The Platte River flows from west to east of Nebraska and confluences to the Missouri River in the east border of Nebraska. The Platte River and its tributaries in the study area have generally good connections with the High Plains aquifer. Extensive groundwater irrigation in the past 60 yr in this area and the projected climate changes make conjunctive use of groundwater and stream water a necessary policy. In south-central Nebraska, some reaches of the river network loses water to the aquifer but other reaches gain water from the aquifer. In this study, eight study sites were selected in the Platte River and its tributaries. Four study sites were located in south-central Nebraska, including one site in the Platte River, and one site in each of the three tributaries: Spring Creek, Lost Creek, and Wood River. These four sites were under losing conditions. Field investigations of the four sites were performed in July and August of 2011. Other four study sites were located in eastern Nebraska. Three sites were in the Platte River and they are near Clarks, Duncan and North Bend; the fourth site was in Clear Creek, a tributary of the Platte River. These four sites were under gaining conditions. The field investigations for these sites were conducted between 2005 and 2012. The sediments

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in the Platte River consist mainly of sand and gravel. The regional groundwater flows from west to east. Figure 1 shows the eight study sites.

2.2 Determination of losing and gaining conditions

Stream water and groundwater temperatures were measured using the Multi-Parameter Testr35 at four study sites during our field work. Groundwater temperature here refers to the temperature measured from sediments about 40 to 50 cm beneath the water–sediment interface. For losing stream, the temperatures of stream water and groundwater will be close to each other because stream water infiltrates into the underlying streambed and into the sediments on both sides of the channel although there will be a time delay of sediment temperature to peak temperature in stream water (Silliman et al., 1995). For gaining streams, the water temperature beneath the water–sediment interface is close to the shallow regional groundwater temperature and the stream water temperature is higher because of the high atmosphere temperature in the summer time. The losing or gaining conditions for the other sites were determined based on the geological and hydrological settings of the study sites.

2.3 Permeameter tests for top-layer streambeds

In this study, in-situ permeameter test method was used to determine the vertical hydraulic conductivity K_v of the top layer of streambed at each site. In-situ permeameter test is cost effective method and it can be conveniently operated in river channels to determine K_v values of the top layer of streambeds while the sedimentary structures of the tested sediments are very little disturbed. The in-situ permeameter test procedures are well documented by Chen (2004) and Genereux et al. (2008). For most of the study sites, 8 to 12 in-situ permeameter tests were conducted to determine the K_v values of the top layer of streambed.

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2.4 Sediment coring

We used Geoprobe direct-push machine to collect sediment cores from the study sites. Geoprobe direct-push machine has two functions. The first function is that it can generate electrical conductivity (EC) log of sediments. The EC values of silt and clay layers are one or two times greater than the EC values of sand and gravel layers due to their difference in mineral composition. Therefore, an EC log can provide the vertical pattern of hydrostratigraphic units very well. During EC logging, a probe was pushed through sediments without the need of a borehole. Thus, this EC logging procedure has small disturbance to the surrounding sediments near the probe. A laptop computer was connected to the Geoprobe system during the logging process and displayed the EC log of the tested streambed on site. The EC log clearly show the patters of coarse sediments (medium-coarse sand and gravel) and fine sediments (fine sand and silt/clay).

The second function is that Geoprobe generates continued sequence of sediment cores. Unconsolidated alluvial sediments were sampled into a 1.5-m long tube when the sampler was driven through the streambeds. The coring tube was transparent. After the core was brought to the ground surface, the lithological patterns of the streambed sediments were examined at test sites and were cross-checked with the patterns of EC logs. In the study sites, the Geoprobe machine got into the river channel when the access was permitted. Otherwise, coring was conducted at the river banks. At each test site, the first core was collected for the depth of $0 \sim 1.5$ m; the second core was collected from the depth of $1.5 \sim 3$ m. Repeating the sampling procedure gave a continued sequence of sediment cores. At each test site, an EC log was produced before sediment coring. The EC logging spot and the coring spot were about one meter apart. Chen et al. (2008) provided details of using Geoprobe for EC logging and sediment coring. The sediment cores from Wood River, Spring Creek, and Clear Creek sites were collected from the bank, about 1 m from the waterline at these test sites. The sediment cores from other five sites were collected from the river channel. These cores were transported back to laboratory for permeameter tests. In-lab permeameter test method

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was used to determine K_v values of these sediment cores from each of the study sites. The in-lab permeameter test method for determining the K_v values of sediment cores was described by Chen et al. (2008). After the K values of the cores were determined, K profiles with depth were plotted.

3 Results

3.1 Temperature and EC values in stream water and groundwater

The sediment temperatures were tested in four study sites and are shown in Table 1. The sediment temperature was 16 °C in Clear Creek measured in August 2011, whereas stream water temperature was 22.3 °C (see Table 1). The regional groundwater temperature was about 12–15 °C in this area. The sediment temperature in Clear Creek was close to the ground water temperature. Thus, Clear Creek was determined to be a gaining stream. The other three study sites in eastern Nebraska were in the Platte River which was under gaining condition. The sediment temperatures in Wood River, Platte River north channel, and Lost Creek are greater than 20 °C and close to the stream water temperature (Table 1). They were determined to be losing streams.

The Multi-Parameter Testr35 was also used to measure the electrical conductivity of the stream water at several sites. The EC values of stream water are higher than those of groundwater in the four study sites (Table 1). The EC values in stream water ranged from 637 to 1360 $\mu S\,cm^{-1}$ whereas these in groundwater ranged from 312 to 546 $\mu S\,cm^{-1}$ (see Table 1).

3.2 K_v for top layer of streambed in losing streams

Streambeds in losing stream reaches often have higher contents of fine-grained materials (silt/clay and fine sand) that fill the interstices of coarse-grained sediments (medium-coarse sand and gravel). This can lead to poorly sorted sediments and lower hydraulic conductivities. Visual examination of the sediments can easily see the mixture nature

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of sand/gravel and fine-grained materials. At the Wood River site and the Platte River north channel site, patches of fine-grained sediments, as well as poorly sorted sand and gravel were observed. These lower permeability silt/clay and fine sand lenses exist in the channel surface but have not formed a continuous clogging layer. The mixture of fine-grained sediments with coarse sediments (medium and coarse sand and gravel) is reflected by a wide range of streambed hydraulic conductivities. For example, in the Wood River test site, ten in-situ permeameter tests were conducted. Four tests encountered silt/clay and fine sand and their K_v values are smaller than $0.6\,\mathrm{m\,d^{-1}}$. The other six tests were conducted in medium-coarse sand and gravel, and their K_v values ranged from 1.4 to $17.1\,\mathrm{m\,d^{-1}}$, indicating permeable sediments. Table 2 lists the minimum, maximum, and median K_v values for the study site. Figure 2 is the box plot showing the distribution of the K_v values. The K_v values fall in six orders of magnitude.

At the Platte River north channel site, five of ten tests encountered the mixture of fine-grained and coarse-grained sediments and had K_v values from 0.05 to $0.56\,\mathrm{m\,d^{-1}}$. The other five tests gave K_v values from 2.5 to $25.9\,\mathrm{m\,d^{-1}}$, indicating high permeability sediments (sand and gravel). The K_v values fall in four orders of magnitude. The minimum, maximum and median K_v values are listed in Table 2. The distribution of the K_v from this site is similar to the pattern for the Wood River site (Fig. 2). The wide range distribution of K_v values probably indicates a transitional phase of streambeds evolving from coarse sediment streambeds to complete clogging losing streams. With the further development of the losing process, more fine particles can be deposited at the channel surface. When the fine-grained patches are connected together, a completely clogged layer may be formed. A sediment sample was taken from a permeameter test point ($K_v = 25.9\,\mathrm{m\,d^{-1}}$) at the Platte North north-channel site and was sieved for grain size analysis. This sample contains 21.2 % of fine sand and 1.8 % of silt/clay; the rest is medium- to coarse-sand and gravel. The content of fine particles in this sample is higher than that for samples from the Platte River in the gaining sites (see the results later).

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The streambeds in the other two sites of losing streams in south-central Nebraska (Lost Creek and Spring Creek) are nearly fully clogged. When the channel is fully silted, a layer of fine-grained sediments covers the channel surface. The K_v values determined from 10 in-situ permeameter tests in Lost Creek ranged from 0.0003 to 0.48 m d^{-1} with a median of 0.12 m d^{-1}. A sediment sample was taken from the spot of a permeameter test in Lost Creek, and the sample was sieved for grain size analysis. Results indicate that this sample consists of 56.8 % fine sand and 4 % silt/clay. A sample from another test point contains 85.8 % of fine sand and 5.5 % of silt/clay. This large amount of fine-grained sediments is in consistent with the lower permeability of the streambed.

At the Spring Creek site, the K_v values range from 0.018 to 0.2 m d^{-1}, with the median value of 0.048 m d^{-1} (Table 2). Generally, when K_v values are smaller than 0.1 m d^{-1}, sediments are not very permeable. At the Wood River and the Platte River north channel sites, 11 K_v values are greater than 1 m d^{-1}; at the Lost Creek and Spring Creek sites, all of the K_v values are smaller than 1 m d^{-1}. The distribution pattern of K_v for the Lost Creek and Spring Creek sites is similar to each other (see Fig. 2), but differs from the pattern of K_v for the other two losing stream sites.

3.3 K_v for top layer of streambed in gaining streams

In contrast, the gaining stream reaches have well sorted and clean sand and gravel in the top layer of streambeds with very small amount of silt and clay (< 1 %). According to Dong et al. (2012), the weight percentage of silt and clay particles (< 0.0625 mm) in 14 sediment samples from the Clear Creek site ranged from 0.1 to 1.9 % with an average of 0.6 %. These types of sediments often have hydraulic conductivity greater than 1 m d^{-1}. For example, in Clear Creek, the K_v values determined from 12 in-situ permeameter tests in streambed in 2010 ranged from 1.2 to 110.7 m d^{-1} with a median of 16.6 m d^{-1}. In the site of the west of North Bend, a total of 48 in-site permeameter tests were conducted in 2008 in a 6 by 8 grid with grid spacing of 1.5 m. The K_v ranged from 22.5 to 50.9 m d^{-1}, with an average value of 33.3 m d^{-1} (a median value of 31.8 m d^{-1}).

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None of the K_v values was smaller than $1\,\mathrm{m\,d^{-1}}$. Eleven in-situ permeameter tests were conducted in the Platte River at the Clarks site, and Fig. 2 shows the distribution of these K_v values. The K_v values range from $14.9\,\mathrm{m\,d^{-1}}$ to $61.3\,\mathrm{m\,d^{-1}}$ with an average of $31.3\,\mathrm{m\,d^{-1}}$. A sediment sample was collected after each of the 11 permeameter tests was conducted. Sieving analysis results indicate that the sediments contain trace amount of silt and clay (< 0.2 %) and a small amount of fine sand ranging from 1.4 to 12.4 % with an average of 6 %. The rest part of these sediment samples consists of medium and coarse sand and some gravel. Fifteen in-situ permeameter tests were conducted in the Platte River near Duncan. The K_v values range from $11.9\,\mathrm{m\,d^{-1}}$ to $53.0\,\mathrm{m\,d^{-1}}$ with an average of $33.0\,\mathrm{m\,d^{-1}}$. Figure 2 shows the distribution of these K_v values. Sieving analysis of sediment samples from the 15 test spots indicate that the streambed contains fine sand ranging from 2.1 to 12.1 % with an average of 4.9 % and has trace amount of silt and clay (compared to 22.2 % of fine sand and 1.8 % of silt/clay for the sample in the Platte River north channel site under losing condition). The rest part of these sediment samples contains medium and coarse sand and some gravel. As one can see from these measurements, the K_v measurements from the gaining streams have a very narrow range of distribution with high values. Note that the median K_v value for the Platte River north site (losing condition) is only $1.6\,\mathrm{m\,d^{-1}}$. Comparing to the median K_v values at the Lost Creek and Spring Creek sites, the median K_v values in the four gaining condition sites are greater by 3 to 4 orders of magnitude.

The K_v pattern for the four gaining stream sites, as shown in the box-plot of Fig. 2, is very similar to each other, particularly for the three sites from the Platte River (Clarks, Duncan, and west of North Bend). The K_v pattern for the four gaining stream sites differs very much to the pattern for the four losing stream sites.

Kruskal-Wallis test was used to determine whether the K_v values from any two test sites belong to the same population. The analysis was performed using the statistical function in MATLAB. For this statistical analysis, the null hypothesis was that all samples were draw from the same population, and the program returned p-values. If the p-value was near zero, it rejected the hypothesis and indicated that at least the median

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value of one group of K_v values was significantly different from the other. When $p > 0.05$ (or at the confidence level of 95 %), it accepted the null hypothesis that the two sets of K_v values were drawn from the same population. The p-values for the Kruskal-Wallis tests are summarized in Table 3.

These p-values indicate that K_v from any test sites of the gaining streams differ from K_v from any single site of the losing stream. In the four gaining-stream sites, the K_v values were drawn from the same population. Among the four losing-stream sites, the K_v values from the Lost Creek and Spring Creek sites were drawn from the same population; the K_v values from the Wood River and Platte River north bank sites were drawn from the same population. However, K_v values from the former two sites statistically differ from the K_v values of the latter two sites. Although the four sites were under losing conditions, the Lost Creek and Spring Creek sites had higher level of siltation. The statistical results are consistent with the streambed hydraulic conditions.

3.4 K_v profiles for losing streams

K_v determined from each sediment core generated by Geoprobe was plotted vs. depth. Thus, one K_v profile was produced for each test site. Figure 3 shows the K_v profiles for the four losing stream sites in south-central Nebraska. All of the K_v profiles show an increasing trend with depth (Fig. 3). In Lost Creek, the top layer of the streambed sediment at the depth interval of $0 \sim 1.5$ m has a low K_v value of 0.00008 m d^{-1}, and the K_v values increase to 0.0012 m d^{-1} and 0.09 m d^{-1} in the next two depths. The five K_v values below the depth of 4.5 m fluctuate in a constant range and they do not show an increase or decrease trend. We interpret that the filtration of fine particles reached to a depth of about 4.5 m in this small creek. The surface-water width across Lost Creek was about 2.7 m in July 2011 during the field work, and the water depth was only 15 cm. These cores were taken from the channel.

At the Platte River north channel site, the five K_v values show an increasing trend with the depth. These five cores were taken from the unconsolidated sediments. The sediment beneath the depth of 7.5 m is an aquitard that distributes extensively in this

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region and separates the unconsolidated Quaternary sediments from the Tertiary Ogallala Group (Chen et al., 2008). Compared to Lost Creek, the overall K_v values in the Platte River are much greater, but the decreasing trend is the same at the two sites. The Platte River at the study site is braided and the channel sediments consist mainly of sand and gravel. The width of the north channel where we conducted this study was about 30 m. The average water depth for the 10 permeameter test spots was 25.6 cm.

For the Wood River and Spring Creek sites, the Geoprobe coring was conducted on the river banks. The river bank was about 1 to 1.5 m above the water. Thus, the first sediment core at the two sites was unsaturated bank materials and the K_v values for the two cores were not included for the analysis. In losing streams, water move laterally in addition to seeping downward as shown by Chen and Chen (2003). Thus, fine particles can filtrate laterally into the sediments below river banks. The two K_v profiles show an increase trend. For the Wood River site, an increase trend is shown for the depth of 1.5 m to 16.5 m. The channel width and water depth were 6.9 m and 16 cm, respectively. An increase trend of K_v with depth is also clear at the Spring Creek site (Fig. 3). The channel width and water depth were 4.6 m and 74 cm, respectively.

For each of the four test sites, the K_v values for the top five sediment cores already indicate a decreasing trend with depth. Table 4 summarizes the minimum, maximum, and median K_v values for the top five cores. The minimum and median values for the Wood River, Lost Creek and Spring Creek sites are all smaller than 0.5 m d^{-1}, indicating low-permeability sediments. The minimum and median values from the Platte River north channel site are much higher. This suggests that in permeable streambeds, a decreasing trend of K_v with depth can be still available when the stream is under losing condition.

3.5 K_v profiles for gaining streams

In gaining streams, the K_v profiles show a decreasing trend with depth (Fig. 4). The cores were taken from the middle of the Platte River at the Clarks and Duncan site in 2005 when this segment of the Platte River was nearly drying up (Chen et al., 2008).

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For the site in west of North Bend, cores were taken in exposed streambed in 2008; at the site of Clear Creek, cores were taken from a very flat bank. Thus, the first core at the two sites was not plotted into the K_v profiles for this trend analysis. In this analysis, only cores taken under the water table were used. When the sediments are above the water table, the hydrodynamics of the losing or gaining process has no longer an impact on the exposed sediments.

At the Clear Creek site, the six K_v values for the depth of $1.5 \sim 9$ m show a decreasing trend. The K_v is $57.5\,\mathrm{m\,d^{-1}}$ for the $1.5 \sim 3$ m depth; it decreases to $1.4\,\mathrm{m\,d^{-1}}$ at the depth of 9 m. At the Clarks site in the Platte River, the eight K_v values decreased from $26.5\,\mathrm{m\,d^{-1}}$ from the $0 \sim 1.5$ m depth to $0.01\,\mathrm{m\,d^{-1}}$ at the depth of $9 \sim 10.5$ m. In the Duncan site of the Platte River, the top layer of the streambed sediment at $0 \sim 1.5$ m depth has a high K_v value of $61.4\,\mathrm{m\,d^{-1}}$; the K_v value becomes $0.3\,\mathrm{m\,d^{-1}}$ at the 9 to 10.5 m depth. In the site of west of North Bend, the decrease trend of K_v is also clear. The core for the $3 \sim 4.5$ m depth was missing at this site and K_v was not able to be determined for this depth. But this did not affect the determination of the decreasing trend of K_v. The six K_v values decreased from $16.9\,\mathrm{m\,d^{-1}}$ in the top to $0.4\,\mathrm{m\,d^{-1}}$ in the bottom of the profile. The minimum, maximum, and median of K_v values for the top five cores are summarized in Table 4.

4 Discussion

Infiltration situation in losing streams can occur under natural conditions or be induced by lowering the groundwater table by adjacent pumping wells (Hiscock and Grischek, 2002). Streambed and the river banks provide filtration functions that lead to deposition of fine particulate matters (organic or inorganic), biological colonization, and chemical precipitation or mineralization. The input and deposition of sediment particles, micro-organisms and colloids, precipitation of iron and manganese oxy-hydroxides and calcium carbonates within streambed reduced streambed hydraulic conductivity (Hiscock and Grischek, 2002). The physical, biological and chemical processes are the driving mechanisms that clog the stream sediments and reduce the sediment pores under losing conditions (Hancock, 2002). Physical process mainly involves settling of fine particulate matters on the water–sediment interface; some fine particles can be transported into the pores of the upper streambed layer depending on the hydrologic condition and sediment structures (Bouwer, 2002; Cui et al., 2008; Stuyfzand et al., 2006; Wett et al., 2002). For example, the accumulation of the fine solids at a Rhine-River riverbank filtration site is limited to the water–sediment interface and chemical precipitation occurred about 10 cm below the interface (Schubert, 2002). Gunkel and Hoffmann (2006) confirmed that in a bank filtration system of Lake Tegel (Germany) algae (mainly diatoms) is adapted to the sediment pore system, has a very high concentration in the upper 5 cm of sediment, and thus, significantly influence the composition of the upper sediment layer. The concentration of algae rapidly decreases below 10 cm. It seems that the effect of the physical, biological and chemical clogging is most significant only in a small depth. But the clogging can reduce the streambed hydraulic conductivity by 10–100 times and thus reduce the hydrological connections between streams and the adjacent aquifers. The filtration efficiency of the streambed depends on several physical, biological and chemical factors, including the sizes of the suspended particles and streambed sediment composition, pore water velocity, pore water pH and ionic strength, and the surface chemical composition of the suspended particles (Ren and Packman, 2002; Karwan and Saiers, 2012). Differences in grain size (and therefore pore size) of the framework exercise a strong controlling influence on the infiltration of fine particles into bed interstices (Frostick et al., 1984).

This study was not aimed at separating the three major clogging processes in the four study sites under losing conditions. We will mainly interpret K_v spatial distribution pattern in losing streams and relate the pattern to filtration process. The reduced K_v in these four losing study sites was probably the combined effects of the physical, chemical and biological processes.

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4.1 Hydrodynamic effects

The motion of pore water provides the principal mechanisms for transport of sediment particles (Davis Jr., 1983) within the sediment matrix. So, the transport direction and deposit position of fine particles are controlled mainly by the hydrodynamic conditions in stream-aquifer systems. Under losing conditions, fine particles suspended in stream water can readily be carried into porous streambeds composed of sediments of sand size or larger, and then deposit due to a combination of gravitational settling and attachment to bed sediment surfaces (Packman et al., 2000a,b). Fine particles preferentially deposit at inflow regions on the streambed surface. Substantial accumulation of fine particles at these inflow locations can plug the uppermost layer of the streambed, affect the bulk porosity (Rehg et al., 2005) and thereby greatly decrease the vertical hydraulic conductivity in streambed. Streambed particle filtration depends on overlying streamflow (Karwan and Saiers, 2012). The concentration of fine particles can be high in stream water during flooding which provides the source of fine articulate matters for clogging process. When the infiltrated water passes through the water–sediment interface and moves further into a depth, the concentration of suspended fine particles in the water reduces gradually. The degree of siltation due to the deposits of clay and colloids then decreases at a larger depth. This water infiltration process in losing segments produces streambeds that contain less fine materials in a larger depth and cause less alteration of the original K in the coarse sediments. Laboratory observation suggested that the fine particle penetration is in a limited thickness (for example, less than 50 cm). Although our field investigation was not designed to detect the penetration depth of the clogging process, the K_v patterns from the study sites probably indirectly indicate that the streambed hydraulic conductivity can be affected to the depth greater than 5 m. Lateral water filtration toward the stream banks can also clog the originally coarse sediments and form a low-permeability zone below the bank. The cores from the Spring Creek and Wood River sites were collected from the bank. The decreasing trend of K_v in the sediments below the river bank at these two sites was believed to be formed by the lateral and downward infiltration process under the losing conditions.

The magnitude of K_v values can reflect clogging degree of the streambed and the penetration depth of the fine particles into the streambed. Among the four test sites under losing conditions, the smallest K_v value of 0.00008 $m\,d^{-1}$ occurred in the top layer of the streambed in Lost Creek whereas the relatively high K_v value of 2.5 $m\,d^{-1}$ occurred in the top layer of the Platte River north channel. According to the results of the in-situ permeameter tests, we believe that the streambed at the Platte River north channel site and the Wood River site are under partially clogged condition (or intermediate clogging) whereas the Lost Creek and Spring Creek sites are reaching the completely clogged stage and the channels at the two sites are covered by fine materials (silt and clay). In the intermediate stage, the streambed sediments are characterized by patchy distribution of silt/clay and fine-sand lenses and display a big spatial variation in streambed K_v values. For example, in the Platte River north channel, the greatest K_v value is about four orders of magnitude higher than the smallest K_v value in the upper layer of streambed. Under the completely clogged condition, the streambed sediments are nearly covered by mostly low permeable sediments in streambed, e.g. K_v values in Lost Creek streambed were mostly (eight out of ten K_v values) less than 1 $m\,d^{-1}$, ranging from 0.00008 to 2.4 $m\,d^{-1}$.

Additionally, we can see from the K_v profiles in Fig. 4 that relatively greater K_v values (greater than 1 $m\,d^{-1}$) mostly occur at about $5 \sim 10$ m depth in the losing streams. The K_v values for the alluvial aquifer in the study area (Chen et al., 2010) ranged commonly from 1 to 10 $m\,d^{-1}$. Therefore, we speculate that the maximum depth of clogging process into the streambeds may be $5 \sim 10$ m. This depth is in accordance with the modeling results of Chen (2007) that the infiltration depth of stream water in streambed was about 8 m.

In gaining streams, the opposite K_v distribution pattern can be attributed to the upward hydrodynamic condition: groundwater feeding streambed by upward seepage. Under the upward flow conditions, fine particles that are strained between coarse

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particles, colloids, or algae become suspended, are lifted out of streambed and then winnowed by the stream flow. With the disappearance of the fine particles, the sediments in the upper layer of streambeds become more unconsolidated and permeable than those in the lower layer. This furthermore results in the greater K_v values in the upper layers (Fig. 5).

4.2 Chemical effects through the deposition of the colloidal particles

The deposition of colloidal particles in a porous medium is relevant in siltation of streambeds (Packman et al., 2000a). Liu et al. (1995) reported that solution ionic strength influences the dynamics of colloidal deposition and transport in heterogeneous porous media. A rise in ionic strength will be benefit for the deposition of colloidal particles. The ionic strength of a solution can be expressed as (Eby, 2004)

$$I = \frac{1}{2}\sum m_i z_i^2 \quad (1)$$

where m_i is the moles per liter of ion i and z_i is the charge of ion i. Ionic strength is approximately proportional to electrical conductivity.

According to the field measurements, the electrical conductivity of water in streambed sediments is smaller than those in stream water at each site (Table 1). In gaining streams, when stream water is fed by groundwater with a low EC value, the EC value in stream water can be decreased in the upwelling zone. Thus, the ionic strength can be decreased. This decrease can results in the increase of the mobility of colloidal particles and prevent them from deposition in the channel surface. This furthermore contributes to the greater K_v value in the upper layer of streambed sediments in the gaining streams. Conversely, in losing streams, when stream water with a higher EC value enters the subsurface, the total EC value in the subsurface environment can increase, resulting in the deposition of colloidal particles. This can contribute to the clogging process in the upper layer of streambed sediments in the losing streams.

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5 Conclusions

We investigated streambed hydraulic conductivity in losing streams and in gaining streams. We first measured streambed K_v in the top layers of the channel sediments from eight study sites, four sites under losing condition and the other four sites under gaining conditions; we then determined the K_v distribution of streambed in a vertical profile at each test site.

We first compared the hydraulic conductivity in the top 50-cm streambed. In gaining streams, the streambeds consisted mainly of sand and gravel and were very permeable. The K_v values were generally greater than $1\,\mathrm{m\,d^{-1}}$, and in the range of 1 to $100\,\mathrm{m\,d^{-1}}$. The median K_v values from the Platte River with gaining conditions are greater than $33\,\mathrm{m\,d^{-1}}$. However, the median K_v value for the Platte River for the losing condition is only about $1.5\,\mathrm{m\,d^{-1}}$. In the losing streams, the streambed consisted mainly of fine sand, silt and clay if the channel is near fully silted, and consisted of poorly sorted sand and gravel which contained silt and clay lenses. The hydraulic conductivities are often smaller than $1\,\mathrm{m\,d^{-1}}$ and can be as small as $0.001\,\mathrm{m\,d^{-1}}$. Statistical analyses indicated that the K_v values from the four sites under losing stream condition are significantly different from the K_v values from the four sites under gaining stream condition. Among the four sites under losing stream conditions, the K_v values from the Lost Creek and Spring Creek sites are significantly different from the K_v values from the other two sites. This difference probably reflects that the clogging level in the former tow sites differ from that in the latter two sites.

The vertical K_v profiles show two opposite vertical distribution patterns between the two types of streams. In the losing streams, K_v increased downward from the channel surface to depth of about 5 to 10 m. This pattern resulted from physical, chemical and biological clogging mechanisms. Fine-grained materials likely deposited in the pores in the top layer of streambed. Less fine-grained materials became available when the water migrated further downward. In the gaining streams, K_v values showed a decreasing trend. The upward flux suspended sediments, enhanced the pore spacing and elevated

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the K_v values in the top layer of streambeds. These mechanisms for elevating K_v become less effective in larger depth.

Original depositional environments controlled largely the framework of sediment materials and thus affected the overall hydraulic conductivity of the sediments. However, post-depositional environments such as stream-groundwater exchange can re-locate fine materials, induce chemical and biological processes, and eventually alter the original hydraulic conductivity. This post-depositional process has a very significant role in changing the magnitude of K_v and the alteration in K_v can reach several orders of magnitude.

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Table 1. Temperatures and EC values tested in study sites.

Test Site	Temperature (°C) Streambed sediments	Stream water	Air	EC ($\mu S\,cm^{-1}$) Stream water	Ground water
Clear Creek	16	22.3	28.5	637	312
Lost Creek	25.5	25.4	31.5	976	384
Wood River	23.6	24	33.1	1360	546
Platte River north channel	26.8	28.9	34.5	824	356

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Table 2. Maximum, minimum, and median values of K_v from the in-situ permeameter tests.

Test Site	K_v values (m d^{-1}) Minimum	Maximum	Median
Wood River	0.0003	17.1	1.5
Platte River north channel	0.051	25.9	1.6
Lost Creek	0.0003	0.48	0.11
Spring Creek	0.018	0.2	0.048
Clear Creek	1.2	110.8	16.6
P. R. North Bend	22.4	50.9	31.8
P. R. Clarks	14.9	60.3	26.5
P. R. Duncan	11.9	53	31.8

Table 3. *p*-values from Kruskal-Wallis test for comparison the similarity of K_v values between two test sites. When *p*-value is > 0.05, the similarity is statistically significant.

Site pair*	*p*-value	Site pair	*p*-value	Site pair	*p*-value	Site pair	*p*-value	Site pair	*p*-value	Site pair	*p*-value	Site pair	*p*-value
I-II	0.392	II-III	0.784	III-IV	0.171	IV-V	0.004	V-VI	0.821	VI-VII	0.034	VII-VIII	0.066
I-III	0.179	II-IV	0.329	III-V	0	IV-VI	0.012	V-VII	0.028	VI-VIII	0.004		
I-IV	0.325	II-V	0	III-VI	0	IV-VII	0	V-VII	0.007				
I-VI	0	II-VI	0	III-VII	0	IV-VIII	0						
I-VI	0.001	II-VII	0	III-VIII	0								
I-VII	0	II-VIII	0										

* I = Platte River-Clarks, II = Platte River-Duncan, III = Platte River-North Bend, IV = Clear Creek; V = Wood River, VI = Platte River North Bank, VII = Lost Creek, VIII = Spring Creek.

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Table 4. Maximum, minimum, and median values of K_v from the top five sediment cores at each test site.

Test Site	K_v values ($m\,d^{-1}$) Minimum	Maximum	Median
Wood River	0.001	1.3	0.34
Platte River north channel	2.54	34.5	8.2
Lost Creek	0.00008	1.3	0.009
Spring Creek	0.0008	10	0.01
Clear Creek	5.6	57.5	19.3
P. R. North Bend	0.72	16.9	1.9
P. R. Clarks	0.01	26.6	5.6
P. R. Duncan	0.83	61.4	13.9

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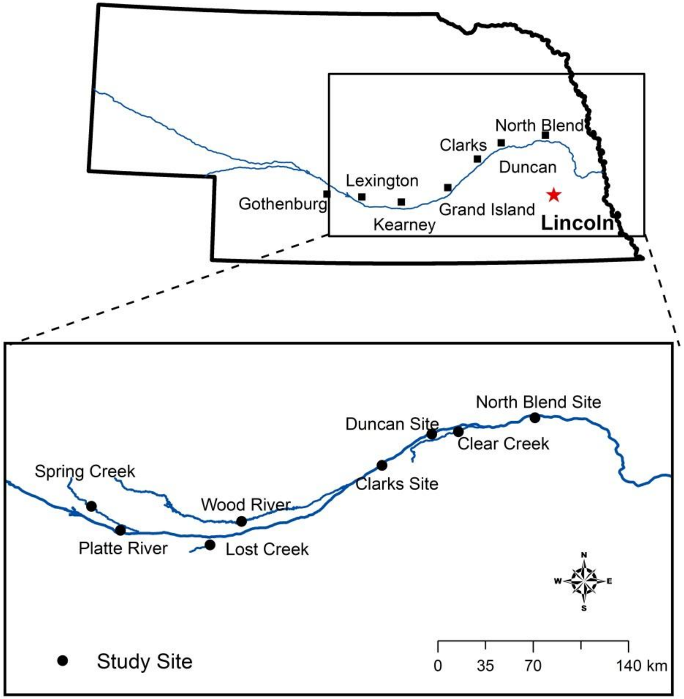

Fig. 1. Location map of eight study sites in south-central and eastern Nebraska. Square symbols indicate nearby towns or cities; dots represent the eight study sites.

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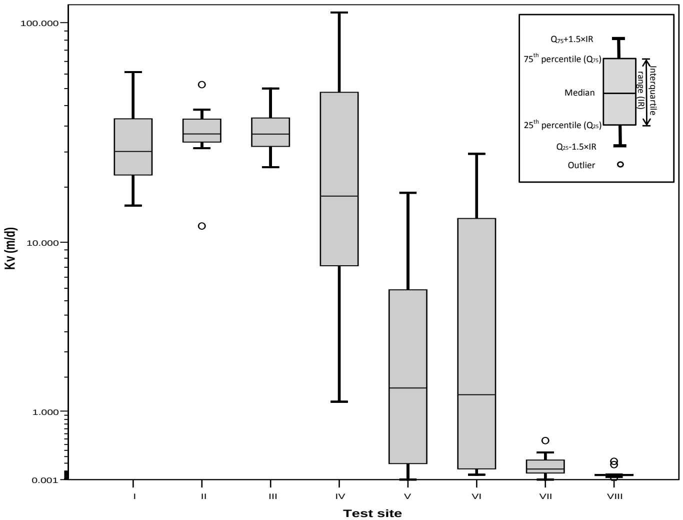

Fig. 2. Box-plot to show the K_v distribution for the eight test sites. The label in the horizontal axis is designated: I = Platte River-Clarks, II = Platte River-Duncan, III = Platte River-North Bend, IV = Clear Creek; V = Wood River, VI = Platte River North Bank, VII = Lost Creek, VIII = Spring Creek

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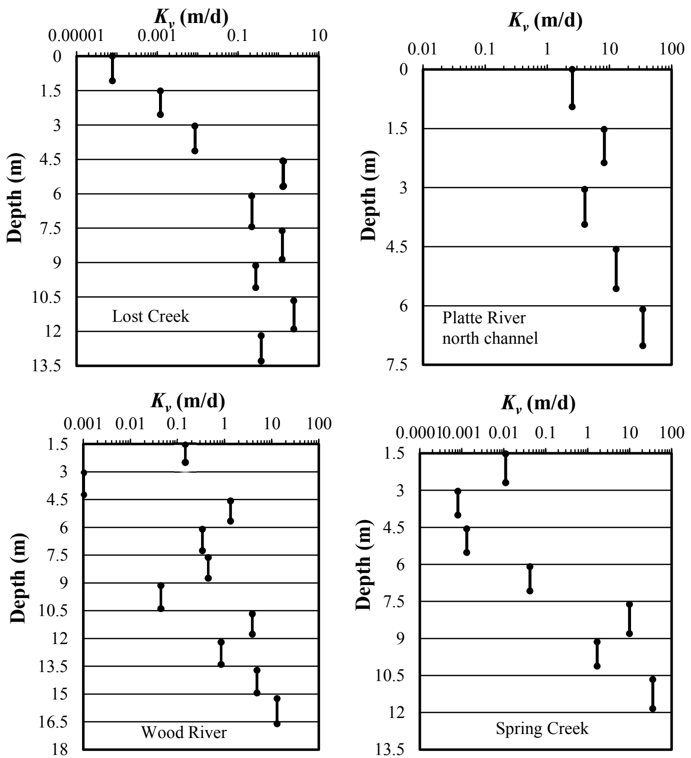

Fig. 3. Distribution of K_v with depth in losing streams for four study sites in the Platte River, Wood River, Spring Creek, and Lost Creek of south-central Nebraska.

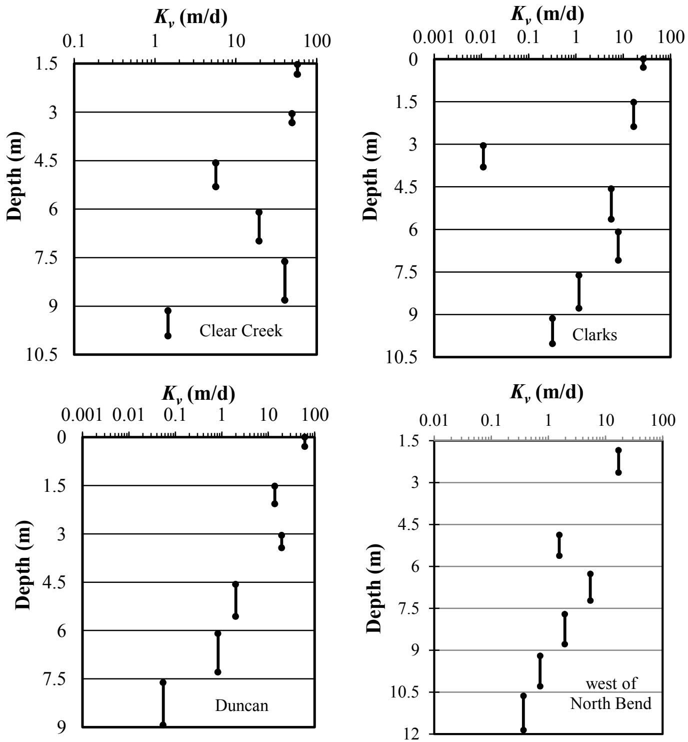

Fig. 4. Distribution of K_v with depth in gaining streams for four study sites in eastern Nebraska. Three study sites were located in the Platte River; the other site was located in Clear Creek.

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