Effect of temperature on streambed vertical hydraulic conductivity

Weihong Dong, Gengxin Ou, Xunhong Chen and Zhaowei Wang

ABSTRACT

In this study, *in situ* and on-site permeameter tests were conducted in Clear Creek, Nebraska, USA to evaluate the effect of water temperature on streambed vertical hydraulic conductivity K_v. Fifty-two sediment cores were tested. Five of them were transferred to the laboratory for a series of experiments to evaluate the effect of water temperature on K_v. Compared with *in situ* tests, 42 out of the 52 tests have higher K_v values for on-site tests. The distribution of water temperature at the approximately 50 cm depth of streambed along the sand bar was investigated in the field. These temperatures had values in the range 14–19 °C with an average of 16 °C and had an increasing trend along the stream flow. On average, K_v values of the streambed sediments in the laboratory tests increase by 1.8% per 1 °C increase in water temperature. The coarser sandy sediments show a greater increase extent of the K_v value per 1 °C increase in water temperature. However, there is no distinct increasing trend of K_v value for sediment containing silt and clay layers.

Key words | clear creek, streambed sediment, temperature, vertical hydraulic conductivity

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INTRODUCTION

Streambed vertical hydraulic conductivity K_v is a key parameter in modeling surface water and groundwater interactions and simulation of contaminant transport in the hyporheic zone. A higher streambed K_v produces a more intensive exchange of water both in quantity and quality. Chen & Shu (2002) reported that a higher streambed K_v induces a higher depletion of stream water due to groundwater pumping nearby streams. It is therefore of great significance for hydrogeologists to estimate streambed K_v accurately and cost-effectively for water resources management. Measurement of K_v can be conducted either in the laboratory or in the field by different methods (Bagarello *et al.* 2000; Butler *et al.* 2007; Dietze & Dietrich 2011). The standpipe method has proven to be an easily performed and economical method to measure K_v *in situ*, on-site or in the laboratory (Chen 2000, 2004, 2007; Cheng & Chen 2007; Song *et al.* 2007; Chen *et al.* 2008; Genereux *et al.* 2008; Dong *et al.* 2012).

For saturated porous sediments, hydraulic conductivity K is derived from Darcy's law and Newton's equation and can be expressed with respect to the fluid and medium properties:

$$K = \frac{k\rho g}{\mu} \quad (1)$$

where k is the intrinsic permeability; ρ is the density of water; μ is the dynamic viscosity and g is the acceleration due to gravity. The intrinsic permeability k is a property of the porous medium independent of the fluid. Hydraulic conductivity for a given medium therefore depends mainly on the fluid viscosity.

The viscosity of water is a function of temperature such that (Fulcher 1925):

$$\mu = A \times 10^{B/(T-C)} \quad (2)$$

where T is temperature (K); $A = 2.414 \times 10^{-2}$ mPa; $B = 247.8$ K; and $C = 140$ K. The viscosity of water decreases with temperature. Equations (1) and (2) indicate that the

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hydraulic conductivity is strongly dependent on water temperature and will increase exponentially with temperature (Darzi *et al.* 2008). The temperature of water entering the soil or variation in soil temperature therefore has a direct impact on soil hydraulic conductivity via the effect of temperature on water's viscosity (Kresic 2007; Ma & Zheng 2010). Early soil column studies also reported that soil hydraulic conductivity increased with soil column temperature; this change was partly or entirely attributed to a decrease in soil water viscosity (Haridasan & Jensen 1972). Many researchers have found that soils showed an increase of one to two orders of magnitude in hydraulic conductivity after freeze–thaw conditions (Othman *et al.* 1994; Konrad & Samson 2000). The magnitude of hydraulic conductivity is therefore strongly temperature dependent as a result of the strong temperature sensitivity of the viscosity of water. The effect of temperature should be taken into account when measuring hydraulic conductivity.

Spatial and temporal variability of temperature in a river system is universal; it is influenced by numerous natural variables such as solar radiation, air temperature, ground temperature, precipitation, surface water inflows and groundwater exchanges (Sinokrat & Stefan 1993). The exchange of water between the river and shallow aquifer plays a key role in influencing temperature not only in rivers, but also in their underlying sediments (Baskaran *et al.* 2009). In a losing system, the sediment temperature is influenced by river temperature as the seepage flux is downwards. In a gaining river, sediment temperature is influenced by groundwater temperature as the flux is upwards (Silliman & Booth 1993; Bendjoudi *et al.* 2005). The temperature of sediment at different depths of streambed is varied because of the exchange of stream water and groundwater in the hyporheic zone (Evans & Petts 1997; Alexander & Caissie 2003; Su *et al.* 2004; Hoehn & Cirpka 2006; Schmidt *et al.* 2006; Baskaran *et al.* 2009). Temperature has been used as a good tracer in the study of vertical hydraulic conductivity variation and interactions between stream water and groundwater (Constantz & Thomas 1996; Ronan *et al.* 1998; Hatch *et al.* 2006; Westhoff *et al.* 2011).

The characteristics of temperature variability of stream water and streambed are well documented in many rivers (Constantz 1998; Conant 2004; Cadbury *et al.* 2008; Leach & Moore 2011). In the Sierra Nevada Mountains, for example, the annual stream temperature variations can range from 0 to 25 °C. In summer, diurnal stream temperature fluctuated by as much as 30–40% of the annual variations in two large streams, due to reduced stream flows and increased atmospheric heating (Constantz 1998). Conant (2004) also observed a 9 °C spatial change in temperatures at both the Pine streambed surface and a depth of 20 cm. Considerable temperature changes of stream water and streambed are obvious both spatially and temporally, and they can affect the K_v values of streambed as mentioned above.

Although the diurnal and seasonal temperature changes in river system and the influence of temperature on hydraulic conductivity are well known, the effect of temperature variations on determination of streambed hydraulic conductivity has not experienced as much interest. Very few existing studies examine the effect of temperature on streambed vertical hydraulic conductivity, except for some studies of temperature effect on soil permeability. The objectives of this study were: (1) to investigate the distribution of water temperature at about 50 cm depth of streambed along Clear Creek sand bar in Nebraska, USA; and (2) to evaluate the magnitude of the temperature effect on K_v of Clear Creek streambed.

METHODS

The determination of streambed K_v involved three steps in this study: *in situ* permeameter test, on-site permeameter test and in-laboratory permeameter test. Details of the test procedures are described as follows.

In situ permeameter test

The *in situ* falling head permeameter test procedure for streambed has been well documented (Chen 2000, 2004; Song *et al.* 2007; Genereux *et al.* 2008; Cheng *et al.* 2010). In this study, a transparent plastic tube of length 147 cm and inner diameter 5.1 cm was vertically pushed to a depth of about 50 cm in the streambed. This depth was chosen at which to conduct a permeameter test for the following two reasons: (1) the active hyporheic zone depth was commonly reported to be about 50 cm (Schindler & Krabbenhoft 1998; Weigelhofer & Waringer 2003); and (2) when the ratio of sediment length in the tube L_v to the inner diameter of the tube D is close to 10, the estimation error of K_v can be minimized by arbitrarily choosing a value of m in Equation (3) (Chen 2004).

The vertical hydraulic conductivity K_v is calculated as (Hvorslev 1951):

$$K_v = \frac{\frac{\pi D}{11m} + L_v}{(t_2 - t_1)} \ln (h_1/h_2) \tag{3}$$

where h_1 and h_2 are the hydraulic heads measured inside the pipe at elapsed times t_1 and t_2, respectively; and $m = \sqrt{K_h/K_v}$ (where K_h is the horizontal hydraulic conductivity of the channel sediment), which is often unknown at the time of computation. Lu *et al.* (2012b) suggested an average value of 2.37 for K_h/K_v at this study site. If $L_v = 10D$, a choice of $m = 1$ or $m = 10$ in Equation (3) gives a very small difference in the result of K_v (Chen 2004). In this study, $m = 2$ was applied in the K_v computation for *in situ* permeameter tests.

On-site permeameter test

An on-site falling head permeameter test was conducted immediately in a water bucket on the stream bank after the *in situ* test was finished. The test used the same sediment core as that used for the *in situ* test.

After the *in situ* test at each location, the tube containing sediment core was pulled out of the streambed following the methods described below. Stream water was poured into the tube to fully fill the tube and a rubber cap was secured on the top of the tube to disconnect the sediment and water inside the tube from the atmosphere. The tube with the sediment core was then slowly pulled out upright from the streambed. This procedure was to prevent sediment dropping from the lower end of the tube. After the tube and sediment were brought out of the stream water, the bottom end of the tube was immediately covered by several layers of fine wire mesh. Water in the tube could seep out but sediment particles could not pass through the mesh. The length of the sediment core was measured. Being held vertically by a tripod, the plastic sediment core liner acted as a container for permeameter tests. Stream water was continuously added to the upper end until the bucket placed under the tube overflowed, which ensured the fully saturated condition of sediment during the falling head test. The water level within the tube fell as the test began. A series of drawdown of the water level was measured and recorded (Chen *et al.* 2008).

For on-site permeameter tests, K_v was calculated according to Darcy's law:

$$K_v = \frac{L_v}{(t_2 - t_1)} \ln (h_1/h_2) \tag{4}$$

Equation (4) does not require the m term used in Equation (3), reducing uncertainty.

The measurement procedure of sediment temperature at 50 cm depth in streambed is described in Dong *et al.* (2012).

In-laboratory permeameter test

After the *in situ* and on-site tests, five of the streambed cores (IV-1-A, IV-1-B, IV-4, IV-5 and VI-3) were transferred to the laboratory for permeameter tests. These five sediment cores consist mainly of sand and gravel, but their structures and sediment compositions are different. The objective of the in-laboratory permeameter test was to examine the dependence of K_v on water temperature changes.

A series of in-lab falling head permeameter tests were conducted on the five sediment cores. During these tests, water temperature in the bucket was adjusted to 10, 15, 23, 30 and 40 °C. Water used in the experiment came from the tap in the laboratory with a temperature of about 23 °C. The desired water temperature was maintained by adding ice or hot water in the bucket. The water temperature was measured by the Multi-Parameter Testr35 during the falling head permeameter test. Air temperature in the laboratory was accordingly set at 10, 15, 23 and 30 °C by the air conditioner during the tests; air temperature at 40 °C was hard to maintain by the air conditioner in the laboratory, so was simply maintained at 30 °C for the permeameter tests at 40 °C water temperature. The impact of air temperature on the falling head permeameter test was limited because the tests for core IV-1-A, IV-1-B, IV-4 and IV-5 lasted no more than 10 min and no more than 20 min for core VI-3. However, by controlling air temperature, the temperature difference between air and water can be minimized which helps to maintain water temperatures during the test.

Before each in-lab permeameter test, water with the same temperature as that in the bucket was poured into the top part of the tube until water in the bucket overflowed. After finishing in-lab falling head permeameter tests, K_v values were calculated using Equation (4). Each permeameter test for each sediment core was carried out three times at a specific temperature in order to reduce experimental bias. The average K_v value produced by the three falling head permeameter tests was regarded as the vertical hydraulic conductivity for each core at a specific water temperature.

STUDY AREA AND TEST SITES

The study area is located in Clear Creek, Nebraska, USA (Figure 1; Dong *et al.* 2012). Clear Creek was chosen for this study based on its two advantages. One is that Clear Creek is a gaining stream according to the *in situ* permeameter tests conducted in 2010 (Lu *et al.* 2012a). For a small creek with shallow water depth, the stream water temperature can be easily warmed due to strong solar radiation in the summer. According to the historic records of the US Geological Survey (USGS), the stream water temperature can reach about 30 °C compared to about 15 °C for groundwater. The water temperature gradient in the vertical direction was obvious in Clear Creek sediment. The other advantage is that an electrical conductivity log and a sequence of sediment cores were collected in the bank with Geoprobe, which suggested unstratified

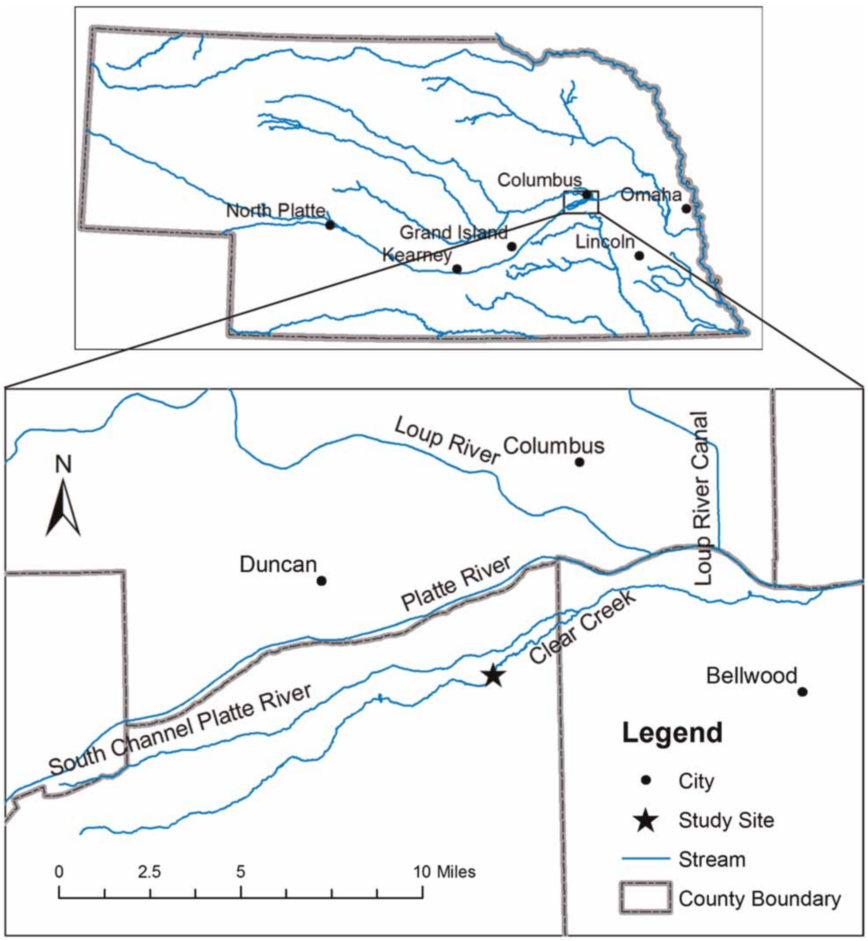

Figure 1 | Location of the study site (modified from Dong *et al.* (2012)).

streambed sediments. However, water temperature differences between stream water and groundwater were not measured in 2010 and on-site permeameter tests had not been conducted.

Fifty-two different locations were selected to conduct both *in situ* and on-site falling head permeameter tests to determine the vertical hydraulic conductivity K_v of the streambed. Figure 2 shows the locations of permeameter tests conducted in the channel of Clear Creek. Twenty-one tests were conducted along the Clear Creek flow direction and close to the left bank, with an interval of 1.6 m between two adjacent locations. The other 31 test locations were arranged in six transects (I–VI) along the creek, with five locations along each transect except for the test location IV-1-B which is close to IV-1-A (Figure 2).

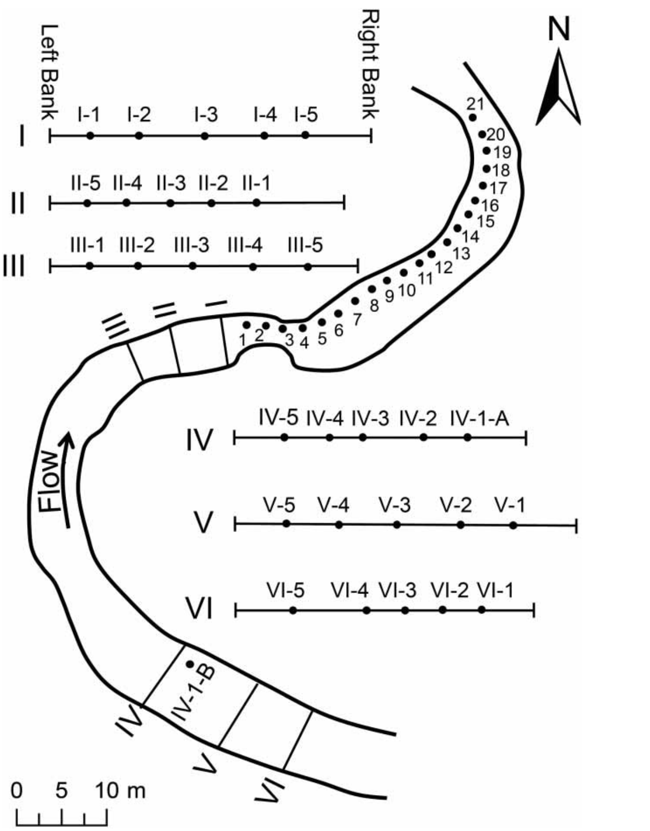

Figure 2 | Schematic of permeameter test locations.

RESULTS

Spatial distribution of K_v

The K_v results from both *in situ* and on-site permeameter tests at the 52 locations are shown in Figure 3. The Kolmogorov-Smirnov tests indicate that both on-site and *in situ* K_v values are from normally distributed populations. As shown in Figure 3, these K_v values have a significant spatial variability. *In situ* K_v values vary from 0.4 to 48.0 m day^{-1} with an average of 15.9 m day^{-1} whereas on-site K_v values fall within the range 0.2–85.0 m day^{-1} with an average of 24.0 m day^{-1}. About 81% (42 of the 52 test locations) of the K_v values obtained by the on-site tests (on-site K_v) are greater than *in situ* values for the same sediment core.

Spatial variation of temperature

Water temperature at the 50 cm depth (the same as sediment temperature at the 50 cm depth) and water

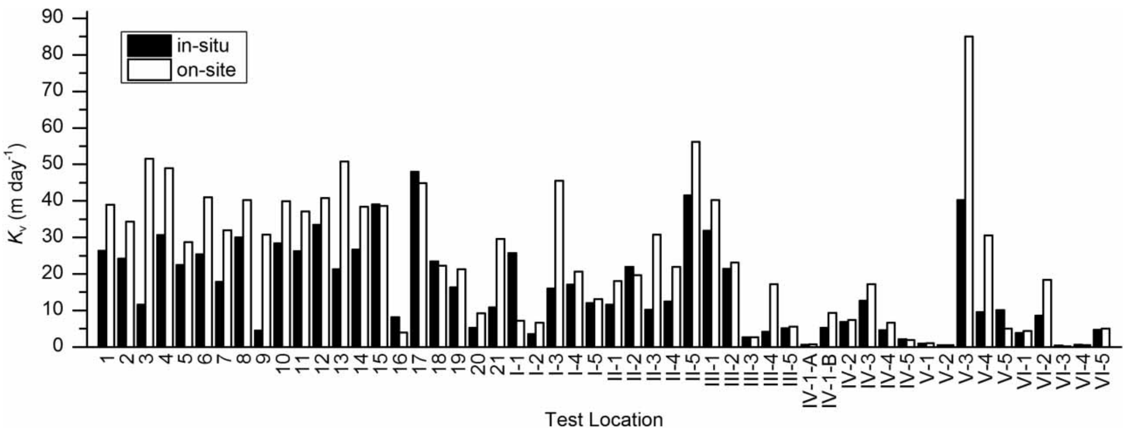

Figure 3 | K_v values from *in situ* permeameter tests and on-site permeameter tests at 52 locations.

temperature of a sample collected in a bucket are plotted in Figure 4 for each test location. The water temperatures at the depth of 50 cm vary over the range 14–19 °C with an average of 16 °C. The water in the bucket, taken from the creek, has temperatures ranging from 19.5 to 30.9 °C with an average of 23.9 °C. The differences between on-site and *in situ* water temperatures ranged from 1 to 15.5 °C with an average of 7.9 °C. In addition, stream water temperature was also dependent upon time of day due to the influences of solar radiation and air temperature (Sinokrat & Stefan 1993). Some of the on-site permeameter tests were performed in the morning while others were performed in the afternoon. Water temperature at the 50 cm depth under streambed is controlled by groundwater, and remains almost constant during the day relative to the stream water (Loheide & Gorelick 2006). Water temperatures of the samples collected in the bucket fluctuate over a greater range (Figure 4).

In-laboratory water temperature effect on K_v

Five sediment cores of different structure and sediment composition were selected on which to conduct experiments investigating the effect of temperature on K_v. The vertical hydraulic conductivity was well reproduced, as similar K_v values were produced in the three falling head permeameter tests for each core at a specific water temperature. The average K_v values are listed in Table 1.

It is evident from Figure 5 that the values of K_v have an increasing trend with an increase in water temperature in each sediment core except for the VI-3 sediment core (which shows a slightly decreasing trend). A thin layer of clay with black organic matter was observed at the bottom end of sediment core VI-3, which was not present in the other four sediment cores. In addition, after the experiments on core VI-3 sediment stratification was observed in the lower part of the sediment core, which can resist the movement of water in the sediments.

DISCUSSION

The data in Table 1 indicate that the K_v values of sediment cores IV-1-A, IV-1-B, IV-4, IV-5 and VI-3 change by 3.1, 1.8, 1.0, 1.5 and –1.5%, respectively, for an increase of 1 °C in water temperature. The average increase in K_v is 1.8% with 1 °C increase in water temperature (if excluding the sediment core VI-3 due to its inverse temperature effect compared to other cores).

Although the five sediment cores consist mainly of sand and gravel, their structures and sediment compositions are different. Sediment cores IV-1-A, IV-1-B and VI-3 have a similar structure with coarse particles in the upper part and fine particles in the lower part of the core. However, the particle size and the length of sediment group are different between the three cores. VI-3 contains a black clay and silt layer about 11.4 cm long in the lower part of the core whereas no clay layer was observed in IV-1-A and IV-1-B. The lengths of the top part of the sediment with coarser particles in IV-1-A, IV-1-B and VI-3 are 24.1, 30.5 and 25.4 cm with total

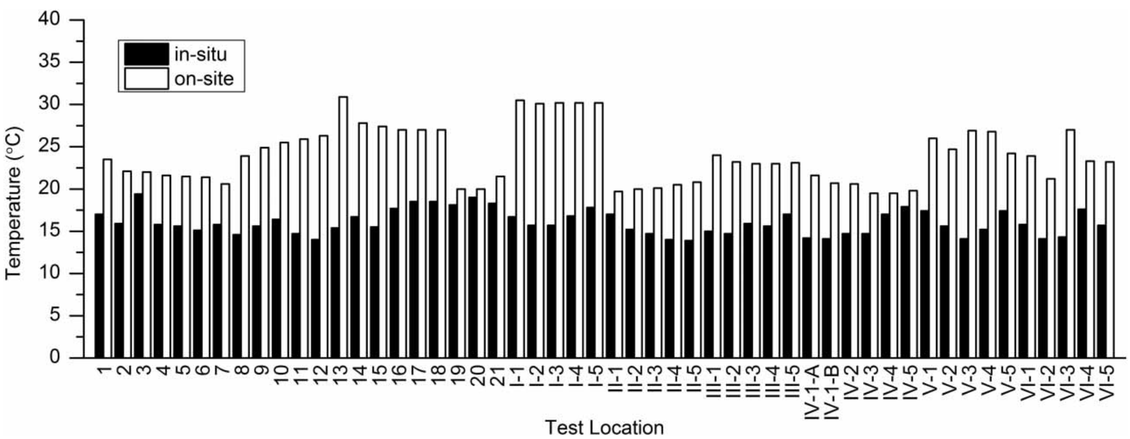

Figure 4 | Water temperatures at the 50 cm depth of streambed (*in situ*) and in the bucket (on-site) for the 52 pairs of tests.

Table 1 | Average K_v values (m day^{-1}) measured in different water temperatures for five samples

	Water temperature (°C)				
Sample	**10**	**15**	**23**	**30**	**40**
IV-1-A	1.2	1.4	2.1	2.2	2.7
IV-1-B	13	15	17.5	18.8	20.5
IV-4	6	6.3	6.3	7.5	7.8
IV-5	1.4	1.5	1.5	1.8	2.1
VI-3	0.8	0.6	0.5	0.6	0.5

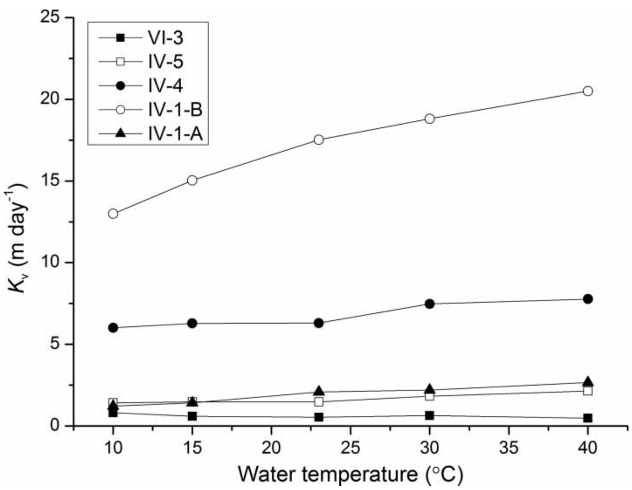

Figure 5 | Changes of K_v values with temperatures for five sediment cores.

sediment lengths of 49.5, 47.0 and 48.9 cm, respectively. The other two sediment cores, IV-4 and IV-5, have an inverse sediment distribution structure with finer particles in the upper part and coarser particles in the lower part. The lengths of upper coarse sediments of IV-4 and IV-5 are 22.9 and 14 cm with total sediment lengths of 52.5 and 51.9 cm, respectively.

The measured K_v values indicate that sediment cores consisting mainly of coarse particles have an obvious increasing trend of K_v values with an increase in water temperature; this is not observed for sediments containing a clay layer, however. Generally, a variation of water temperature causes a viscosity change, therefore affecting K_v. Gases such as CO_2 and CH_4 were possibly generated by organic matter in the lower part of the VI-3 core with a corresponding increase in water temperature (Schindler & Krabbenhoft 1998). The generation of gases can interfere with water infiltration in the tube. Further, water temperature may have an effect on the clay structures and compactions in our experiment. High temperatures can cause swelling of the clay structure and therefore partly obstruct the soil pores (Hansen *et al.* 2012). Our conjecture is that these effects predominated the change of hydraulic conductivity compared to water viscosity. The K_v value of core VI-3 therefore shows a slight deviation from the expected trend of an increase with increasing water temperature.

In this study, the sediment temperature at the 50 cm depth of the streambed represents water temperature during *in situ* tests, whereas water temperature in the bucket represents water temperature in the on-site test. As shown in Figure 4, on-site water temperature is higher than *in situ* water temperature for each paired test. Because the streambed upper sediments (about 50 cm in depth) consist mainly of sand and gravel, most (about 81%) of the K_v values increased with an increase in water temperature when the cores were transferred from *in situ* tests to on-site tests. However, the increase extents are very different. For example, although the water temperature difference is only 1 °C between *in situ* and on-site tests for location 13, the on-site K_v increases by 77% compared with the *in situ* K_v. In contrast, although the water temperature difference is more than 5 °C, on-site K_v values are very close to *in situ* K_v, for example, at locations III-3, V-2, and VI-4. The average increase of on-site K_v is 12% for a 1 °C increase in water temperature, compared with *in situ* K_v. The difference in increase between on-site K_v and *in situ* K_v may be caused by the difference of coarse particle content as suggested by the in-lab test results. Ten on-site K_v values are smaller than *in situ* K_v. The reduction in the 10 on-site K_v values with water temperature increase may be a result of the high clay content in the cores as suggested from the in-lab test results of core VI-3.

To examine the effect of the water temperature change on the difference between *in situ* K_v and on-site K_v, the on-site K_v values were recalculated using Equations (1) and (2) on the basis of *in situ* K_v values for the 52 test locations. We assumed that the parameters k, ρ, μ and g in Equation (1) were constant for the same sediment core. Thus, a relationship between on-site K_v (K_{v-O}) and *in situ*

K_v (K_{v-I}) can be established:

$$K_{v-O} = K_{v-I} \times 10^{\frac{B}{T_I - C} - \frac{B}{T_O - C}} \quad (5)$$

where T_I and T_O are water temperatures in the *in situ* and on-site tests, respectively. Table 2 lists K_{v-O} for the first 21 test locations.

The results show that all of the K_{v-O} values are greater than K_{v-I} values for the 52 tests after the *in situ* K_v was adjusted based on the on-site test water temperature. The K_{v-O} values increase by 2–44% with an average of 22% for each test, compared to the K_{v-I} values under the influence of water temperature only which increase by 2.5–2.8% with an average of 2.7% for a 1 °C increase in water temperature. The increase in temperature obviously contributes to the increase of K_v in streambed sediment.

Table 2 | Measured *in situ* K_v (K_{v-I}) and calculated on-site K_v (K_{v-O}, calculated using Equation (5)) for the first 21 test locations

Location	K_{v-I} (m day^{-1})	K_{v-O} (m day^{-1})	Difference $D = (K_{v-I}-K_{v-O})/K_{v-I}$ (%)	T_I (°C)	T_O (°C)	Difference $D/(T_O-T_I)$ (% °C^{-1})
1	26.4	30.9	17	17.0	23.5	2.6
2	24.2	28.2	17	15.9	22.1	2.7
3	11.6	12.4	6	19.4	22.0	2.5
4	30.7	35.4	15	15.8	21.6	2.7
5	22.5	26.0	16	15.6	21.5	2.7
6	25.4	29.7	17	15.1	21.4	2.7
7	17.8	20.1	13	15.8	20.6	2.6
8	30.0	37.7	26	14.6	23.9	2.8
9	4.5	5.6	25	15.6	24.9	2.7
10	28.4	35.3	24	16.4	25.5	2.7
11	26.3	34.5	31	14.7	25.9	2.8
12	33.5	45.2	35	14.0	26.3	2.8
13	21.3	30.6	44	15.4	30.9	2.8
14	26.7	34.7	30	16.7	27.8	2.7
15	39.1	52.0	33	15.5	27.4	2.8
16	8.2	10.2	25	17.7	27.0	2.6
17	48.0	58.6	22	18.5	27.0	2.6
18	23.5	28.7	22	18.5	27.0	2.6
19	16.3	17.1	5	18.1	20.0	2.5
20	5.2	5.3	2	19.0	20.0	2.5
21	10.9	11.8	8	18.3	21.5	2.5

Nevertheless, other factors such as packing condition also contribute to the greater on-site K_v than *in situ* K_v. During the passage of the tube through the streambed, there exists friction between sediment and the wall of the tube. This can enhance compaction of the sediment in some cases (Chen *et al.* 2009). In order to minimize the influence of compaction on K_v, the wall of the plastic tube was very thin. Its thickness was smaller than 2 mm and the bottom end of the tube was beveled in the permeameter test in this study. We did not focus on the influence of packing condition on streambed K_v in this study, but only water temperature.

CONCLUSIONS

Measurement of K_v by falling head permeameter test can be conducted both *in situ* and on-site for streambed sediment. However, on-site K_v is usually greater than *in situ* K_v in Clear Creek due to the higher on-site water temperature.

In-laboratory tests indicated that the K_v value increased by 1.8% on average with a 1 °C increase in water temperature. Sediments consisting mainly of coarse particles have an obvious increasing trend in K_v with increasing water temperature (except for sediment containing a clay layer).

The on-site K_v recalculations showed that the values increased by 2.7% on average for a 1 °C increase in water temperature, compared with *in situ* K_v after adjusting for the on-site test temperature. This further demonstrated that the variation of water temperature in a river system has a direct impact on streambed hydraulic conductivity via the changes in water viscosity. This paper presents our preliminary findings of the temperature effect on determination of streambed hydraulic conductivity. Such effects should be considered in future modeling work for a higher-accuracy representation of the stream–aquifer interaction. However, more work is required in order to produce a more complete theory of the relationship between temperature and streambed K_v, which will be an extension of this study.

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