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HYDROPHYSICAL PROCESSES

Can Hydraulic Conductivity of Fluvial Sediments be Informed by Spectral Reflectance?

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Abstract—This study explores the statistical relationship between spectral reflectance and hydraulic conductivity (K) of fluvial sediments in two Nebraska rivers. The spectral reflectance curves of sediments are obtained through hyperspectral instruments under controlled conditions. The K values are determined by three different methodologies, grain size analysis, an in-situ permeameter test, and a lab permeameter test. The in-situ permeameter tests calculate vertical K values (K_V), whereas grain size analysis and lab tests and grain size analysis generate non-directional K values. The results show that the lab permeameter tests of repacked sediments present greater hydraulic conductivity values than in-situ tests. The non-directional K values derived from 7 empirical equations, Hazen, Slicher, Terzaghi, Beyer, USBR, Kozeny, and Sauerbrei, correlate well with the in-situ K_V values. Site specific coefficients in 7 equations are developed for the study sites. Correlation analysis is conducted aiming to establish the connection between hydraulic conductivity and spectral reflectance. Inverse trends are found between the reflectance and K values determined by Hazen, Beyer, USBR, and Sauerbrei formulae where particle size distribution is considered to be a key factor. Furthermore, four linear models are developed based on the relationship between grain size derived K and reflectance. The models are used on dried surface channel sediments in the Platte River for predicting K values as a pilot test and proved to be applicable. As direct measurement of hydraulic conductivity can be costly and time-consuming, remote sensing informed hydraulic conductivity of streambed sediments in droughts can be a promising application with further study.

Keywords: hydraulic conductivity, spectral reflectance, particle size distribution, linear regression

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INTRODUCTION

Streambed hydraulic conductivity (K) is an essential parameter in studying stream and groundwater interactions. After years of exploration, researchers have developed several methodologies for estimating K values. Generally, there are four groups of techniques: pumping tests [11], slug tests [1, 13, 23], permeameter tests [3, 4, 8, 10], and grain size analyses [19, 20, 22]. All the above methods offer hydraulic conductivities of point samples.

Soil reflectance is a cumulative property which derives from inherent spectral behavior of the heterogeneous combination of mineral, organic, and fluid matter that comprise soils [21]. Most of the previous studies have focused on predicting soil properties based on spectral reflectance, such as organic matter [12], water content [14], soil color [15, 17], chemical compound [2], and particle size distribution [16]. Shepherd and Walsh [18] developed a spectral library for quantifying soil property and they asserted that particle distribution is strongly related to spectral reflectance. Goldshleger et al. [7] used an artificial neural network (ANN) to assess the infiltration rate of soil samples from Israel and the US and provided a reliable method for predicting infiltration rate from spectral reflectance ($r^2 = 0.91$).

Few studies have attempted to associate fluvial sediment permeability with spectral reflectance (REF). In this study, the in-situ, lab permeameter tests, and grain size analyses were utilized to estimate the hydraulic conductivity of sediments that were collected on the river streambed and point bar deposits. The same sediments were scanned through a hyperspectral instrument to obtain their spectral reflectance. Our research questions are (1) how hydraulic conductivities determined by different methods vary from each other? (2) Is there any connection between hydraulic conductivity and spectral reflectance of fluvial sediments? (3) if there is, can hydraulic conductivity be estimated by spectral reflectance?

METHOD

Study Location

In this study, four sites are chosen to conduct the experiment. Three sites are on Platte River of eastern Nebraska and one site is on Clear Creek, a small tributary to the Platte River. The Platte River, originating from Rocky Mountains, flows from east to west across the whole Nebraska state. The Platte River in the study area is wide and shallow. Nebraska experienced a severe drought in the summer of 2012, which led to widespread exposure of the streambed. Some segments of the Platte River were completely dried up. Under normal conditions, the water depth in the channel is approximately 1 m above streambed. While the drought in 2012 is a catastrophe to river ecosystem, it provides window to study streambed hydraulic conductivities. The width of the Platte River at the study sites is approximately 285 m and the water table ranges from 0.15 to 0.45 m below the streambed surface at the time of field investigation. We perform the experiments in the Platte River near the towns of Clarks, Duncan, and Silver Creek in eastern Nebraska US. The three sites cover about twenty miles of main stem of the Platte River before its confluence with the Loup River.

Clear Creek is a long but narrow tributary of the Platte River. The average channel width and water depth in the stream are 8.0 and 0.31 m, respectively, and the stream water level gradient is about 3‰. Clear Creek is a typical meandering stream and point bars are deposited inside the river bend. Our study location is about 10 km southwest of Columbus, NE, which is close to the former three sites.

In-situ Permeameter Test for Vertical Hydraulic Conductivity (K_v) and Sediment Sampling

Because of the 2012 drought, the Platte River is completely dry, and the groundwater table declines in the study area. In order to reach the saturated sediments below the channel surface, the top streambed sediments are dug out until the water table is presented. We wait for a few minutes until the water table becomes stable. After that, a permeameter test is conducted on the saturated sediments below the water table. 11 (Clarks Creek), 14 (Duncan Creek), and 15 (Silver Creek) point permeameter tests are conducted on the saturated sediments beneath the top layer of dried streambed. Afterwards, the same sediments are collected and taken back to the laboratory at the University of Nebraska-Lincoln. In addition to in-situ permeameter tests, the dried channel surface sediments at the Duncan site are also sampled along and across the channel. At Clear Creek, we perform 14 in-situ permeameter tests to the sub-surface saturated sediments on the point bars and gather the original sediments to the lab. The sampling strategies for Clear Creek point bars are identical to the Platte River dug-out holes, where the saturated sediments are all below the ground surface. In this paper, the hydraulic conductivity, grain size data, and sediment samples of Clear Creek are collected by Dong et al. [5].

The test procedure is thoroughly described by Chen [3]. A transparent tube is inserted into the saturated sediment in the dug-out hole around the same depth and water is filled to the top of the tube. The length and diameter of the tube are 58.5 and 2 inches, respectively. The length of sediments ranges from 19 to 26 inches. During each test, we record 6–8 water level readings and the elapsed time after the water table in the tube begins to drop. The K_v value is calculated using Darcy's Law hereafter.

After each permeameter test, we cover the top of tube using a rubber cup and pull out the transparent tube filled with original streambed sediments for further examination. For every individual sediment sample, it would go through the chain of spectral process for reflectance (REF), grain size analysis for non-directional hydraulic conductivity calculation (K_g), and lab permeameter test for hydraulic conductivity (K_{lab}).

To test the regression model between K and REF, sediment samples are collected on the dried streambed surface at the Duncan site for predicting K values using reflectance. The width of the river is about 285 m and surface samples are collected every 15 m across the channel. Along the river, the sediments are sampled every 30 m. We draw a 30 × 30 cm square at each sampling point and grab the surface sediments to the depth of 2.5 cm. Forty-four samples are obtained in total: 19 from the transect and 25 from the river-parallel direction. These samples are also brought back to laboratory for REF, and K_g experiments.

Table 1. Available data from the study locations (K_v—represents vertical hydraulic conductivity, K_g—represents non-directional hydraulic conductivity determined by grain size analysis, REF—represents spectral reflectance, K_{lab}—represents lab permeameter test value for hydraulic conductivity)

Study Site	Sample Size	Available Datasets
Clear Creek Point Bars	14	K_v, K_g, REF
Platte River Dug-out Holes (Clarks, Silver Creek and Duncan)	40	K_v, K_g, K_{lab}, REF
Platte River Dried Streambed Surface (Duncan)	44	K_g, REF

Spectral Process for REF

We collect the spectral reflectance data in the Center for Advanced Land Management Information Technologies (CALMIT) Spectroscopy Lab at University of Nebraska-Lincoln, using an Ocean Optics USB 2000 hyperspectral field instrument. The CALMIT lab is an all-black room to avoid any environmental reflectance and it is equipped with an instrument platform. The USB 2000, a fiber optic system, uses charge coupled device to record light in 2048 spectral bands ranging from 350 to 1000 nm from a National Institute of Standards Technology (NIST) traceable uniform light source. The field of view (FOV) of the fiber optic is 25°. The wavelength range of the spectral scanning from 350 to 1000 nm is targeted in this study.

In this experiment, sediment samples from the Platte River that experienced in-situ permeameter tests, from the Duncan site channel surface, as well as from Clear Creek point bars are all included. They are oven-dried for 48 h maintaining a temperature of 230°F and evenly distributed by crushing the clogs. The sediment samples are placed in a black container directly after drying with a diameter of 88 cm without using a desiccator. According to the FOV, the sensor is set to the height of 114 cm above the sediments, so that we could gain a 50-cm view to avoid the noise around the margin of the container. We use a calibration panel made of SpectralonTM (Labsphere, Inc., North Sutton, NH) and calculate the ratio of raw data to the calibration data as the reflectance. In order to reduce the position bias, we rotate the container 90° after each scanning and the measurement is taken four times per sample.

Grain Size Analysis for K_g

Grain size analysis is performed on the same sediment samples after spectral reflectance acquisition. Eight sieves are chosen for the sieving process, with pore diameters of 4, 2, 1, 0.6, 0.5, 0.25, 0.125, and 0.063 mm. The sieving process is set for 5 min and a cumulative weight percentage curve is plotted for each sample. Then, hydraulic conductivity-K_g values are calculated using eight empirical methods, including Shepherd [19], Hazen, Slicher, Terzaghi, Beyer, USBR, Kozeny, and Sauerbrei [9, 22]. The effective grain diameter (d_w), porosity function (ψ_n), and dimensionless coefficient (C) vary among the eight formulae. Each method provides an applicable range of dimensionless coefficient and C is determined by depositional environment. At this stage, we adopt the dimensionless coefficients based on the study from Song et al. [20]. Since the K_g value is determined by particle size distribution and empirical formulae, it does not represent any particular orientation.

Lab Permeameter Test for K_{lab}

The lab permeameter test is proposed by Chen et al. [4] and generates K values using Darcy's Law. In our study, the loose sediments from the dug-out holes of the Platte River are poured into a transparent tube and experienced lab permeameter test. The tube is held by a tripod. One end of the tube is covered by layers of fine plastic screen and is submerged into a basket which is full of water. For the open end, water is filled to the top and the drawdown of water table is recorded for calculating K. The significant difference from in-situ experiment is that samples for the lab tests are thoroughly dried and mixed due to the grain size analysis and spectral process. As a result, the original sediment structure is destroyed and K_{lab} values represent neither vertical nor horizontal hydraulic conductivity.

Outputs from Field Tests and Lab Experiments

Table 1 summarizes the available data including hydraulic conductivity and reflectance for all sediment samples. It is vital to point out that all sets of data in one study location are specific to one set of sediment samples. The data are comparable within each site. For the three sites in the Platte River, each sample that first underwent in-situ permeameter test is examined later by spectral scanning, grain size analysis, and in-lab permeameter test. These tests give K_v, K_g, K_{lab}, and REF for each sample. For Duncan surface site, only grain size analysis and spectral scanning are conducted. For Clear Creek site, lab permeameter test was not performed.

RESULTS

Comparison of Three Sets of Hydraulic Conductivity

There are three sets of hydraulic conductivity values for sub-channel saturated sediments in the Platte

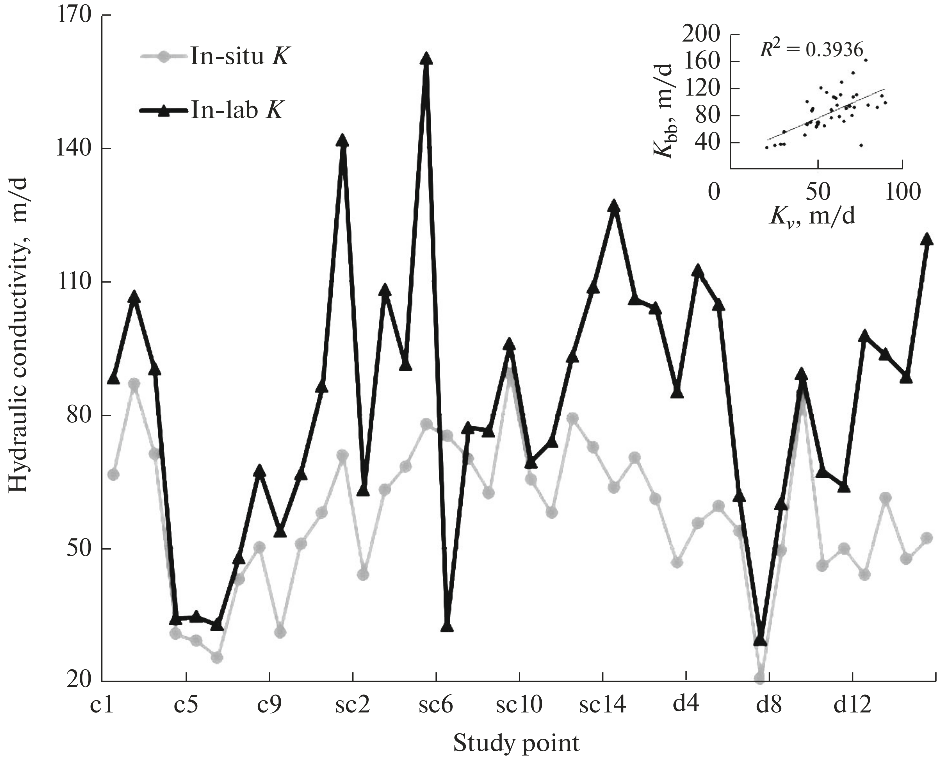

Fig. 1. Plot of K_v and K_{lab} value for sub-channel saturated sediment in the Platte River.

River: K_v, K_g, and K_{lab}. A two-step analysis is used to investigate the inter-connection among the three sets of K values. The correlation and linear regression packages in "R" is used in the data analysis.

Firstly, a correlation analysis between K_{lab} and K_v is conducted. Result reveals that the correlation between K_v and K_{lab} is observable, yet not strong. The graph on the right corner of Fig. 1 tells that the sample points follow the general increasing pattern, but they are scattered around the trend line. The linear correlation coefficient (r^2) is 0.39 and the Pearson's R value is 0.63. In the same time, it can be observed from Fig. 1 that K_{lab} values are generally larger than K_v values except for sc6 site. The average K_{lab} value of the three sites is 82.7 m/day, which is almost 1.5 times larger than the average K_v value of 57.6 m/day. It is recognized that the hydraulic conductivity values increase from layered sediments to interrupted and loose sediments.

Secondly, eight sets of K_g values for saturated sediment samples in the Platte River are plotted with K_v values (left portion in Fig. 2). Poor correlation is learned between K_g determined by the Shepherd method and K_v, with r^2 equals to 0.01. Except for the Shepherd line, the trend of each set of K_g values, fits well with the trend of K_v values (bold black line), although the magnitude differs. The maximum value of r^2 is 0.71, found between K_g determined by the Beyer method and K_v. Other r^2 values range from 0.42 to 0.69 between K_v and K_g calculated by six methods. Although the correlations between K_v and K_g determined by seven methods seem strong, the magnitude of K_g values differs among those methods because the adopted dimensionless coefficients (C) in empirical formulae are from literature. Owing to the unique depositional environment, site-specific C values are generated in K_g calculation for the Clarks, Silver Creek, and Duncan sites. The least square method is selected to derive experimental-based coefficients for empirical equations by minimizing the difference between K_g and K_v and find optimal solutions for C values in the study sites. The result is notable. The right portion of Fig. 2 presents the seven sets of revised K_g with K_v value. The average difference between each revised K_g and K_v values varies from 0.09 to 5.53 m/d, which demonstrates that the C values work well in each formula. Table 2 sums up the adjusted C and correlation coefficients (linear and Pearson's) between K_v and revised K_g for the Clarks, Silver Creek, and Duncan site. Because in-situ permeameter test can be labor-intensive, this study provides a good reference of dimensionless coefficients in seven empirical formulae, located at the Platter River, which can be applied to estimate vertical hydraulic conductivity through grain size analysis in future research, such as regional groundwater modeling, study of surface water-

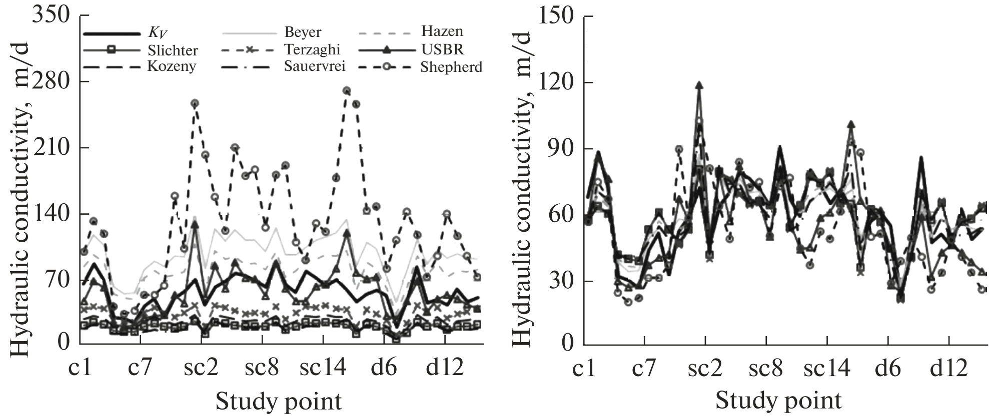

Fig. 2. Plot of K_v with K_g (left) and revised K_g (right) for sediments in the Platte River.

groundwater interactions, estimation of K_v values in nearby watersheds etc.

Relationship Among K_v, K_g, and REF

An effort is made to determine the connection between REF and two sets of K: K_g and K_v. The fiber optics system collects spectral bands from 350 to 1000 nm. The reflectance at 400, 500, 600, 700, 800, 900, and 1000 nm (REF) are chosen for examine the linear relationship with K_v and K_g. The statistical results from 400 to 1000 nm are very similar as the soil reflectance curve is smooth and increases from 350 to 1000 nm without cusp nodes. To avoid repeating identical results, REF at 400 nm is used as a representative in the following section.

Correlation analysis between K_v and REF is conducted for sediment samples from Clear Creek point bars and the Platte River dug-out holes. A vague inverse relationship between K_v and REF is observed in upper part in Fig. 3. The K_v value is likely to increase when the reflectance at 400 nm decreases. The Pearson coefficient between REF and K_v values is 0.23 for the Platte River sub-channel and Clear Creek point bars sub-surface sediments. Subsequently, correlation analyses between REF and 7 sets of calculated K_g values using empirical equations are performed. K_g using the Shepherd method is not included since the site-specific C values is not generated. The results indicate that there are strong inverse relationships existing between REF and K_g value determined by 4 empirical formulae, which are Hazen, USBR, Sauerbrei, and Beyer. The Pearson's r values between REF and K_g are −0.41, −0.61, −0.64, and −0.55 at the Clear Creek and −0.42, −0.65, −0.43, and −0.57 at the Platte River, respectively. An attempt is made to establish statistical relationships between K_g and REF that it could be applied to estimate hydraulic conductivity on a broader spatial scale based on reflectance. The linear relationship between REF and K_g of the Hazen, USBR, Sauerbrei, and Beyer are used in the following K_g prediction (Table 3).

K_g Prediction for Surface Sediment Samples

Based on the established linear relationship between K_g and REF, the samples collected from the channel surface at the Duncan site are used for pilot application. Forty-four surface samples are included in this test. The spectral reflectance data of sediment samples are obtained in the CALMIT lab. Four linear models derived by the Hazen, USBR, Sauerbrei, and Beyer methods (Table 3) are applied for predicting K

Table 2. Revised coefficients of 7 empirical formulae on the Clarks, Silver Creek and Duncan sites

Method	General C	Clarks's C	Silver Creek's C	Duncan's C	r^2	Pearson's R
Hazen	0.0006	0.000414	0.00046	0.00041	0.71	0.85
Slichter	0.01	0.024888	0.030203	0.02658	0.61	0.78
Terzaghi	0.0084	0.012249	0.01516	0.01327	0.58	0.76
Beyer	0.0006	0.000353	0.000368	0.00033	0.72	0.85
USBR	0.00048	0.000582	0.000436	0.0004	0.46	0.68
Kozeny	0.0083	0.016149	0.019567	0.01723	0.61	0.79
Sauerbrei	0.00375	0.011203	0.011689	0.01051	0.61	0.78

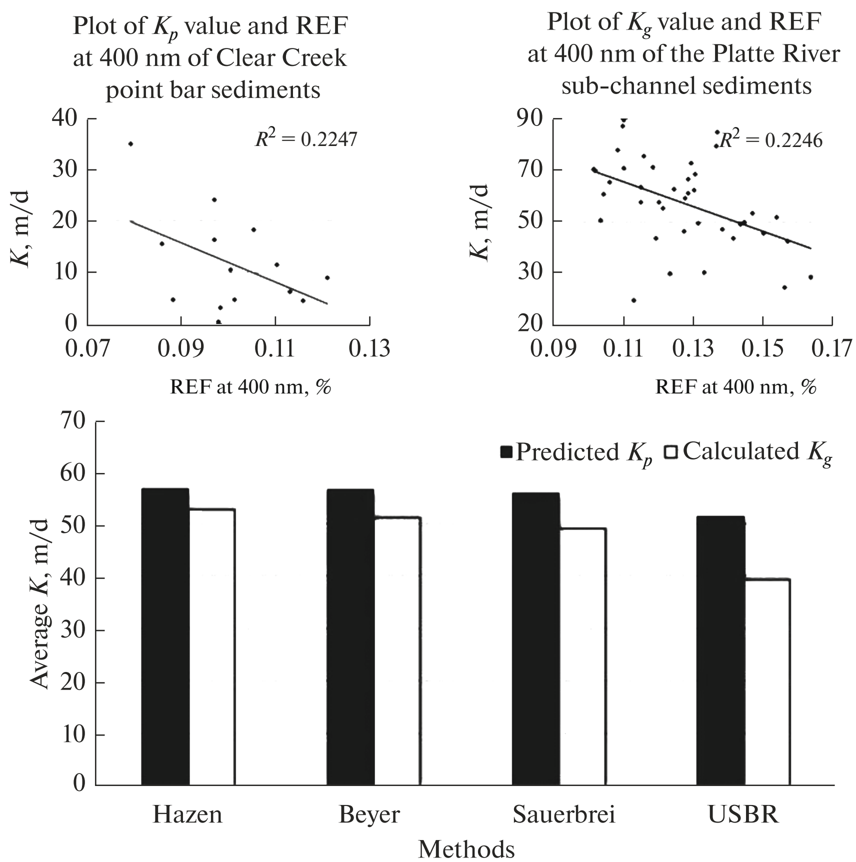

Fig. 3. Plot of vertical hydraulic conductivity with spectral reflectance of fluvial sediments and Average predicted K_p using five methods and K_g values for surface samples of the Duncan site.

(K_p) values using REF at 400 nm. The grain size analysis is performed on the surface samples and K_g values are calculated using same empirical equations with site-specific coefficients. Upon comparison of K_g and K_p, the results show that four linear models provide reasonable results in predicting K values (lower part in Fig. 3). The percentage differences between the averages of K_p and K_g are less than 23.4%, which corroborates the suitability of four linear models in estimation of hydraulic conductivity for Duncan site. Hazen, Beyer and Sauerbrei methods give smaller percentage differences between K_p and K_g values, which are less than 12%. USBR method presents the highest Pearson's R values between K_g with K_p, which is 0.62.

DISCUSSION

Comparison of in-situ and Lab Hydraulic Conductivity Measurements

The comparison of in-situ and lab permeameter tests suggest that the K_{lab} values are greater than K_v values for 39 out of 40 samples. The average K_{lab} value is almost 1.5 times larger than K_v value. This phenomenon could be explained from a microscopic view of the sediments (Fig. 4). In a natural depositional environment, tabular particles are commonly packed and aligned with their long axes perpendicular to the dominant stress orientation, acting as obstacles for vertical water flow (see the left site in Fig. 4). In contrast, when the layered sediments are dried, shaken, and mixed,

Table 3. Derived linear models for predicting K using spectral reflectance at 400 nm (Y—the predicted K value, m/d; X—the spectral reflectance at 400 nm, %)

Linear Model	Hazen	Beyer	USBR	Sauerbrei
Equation	$Y = -360.2X + 103.5$	$Y = -461.3X + 116.3$	$Y = -865.7X + 163.8$	$Y = -413.3X + 109.5$

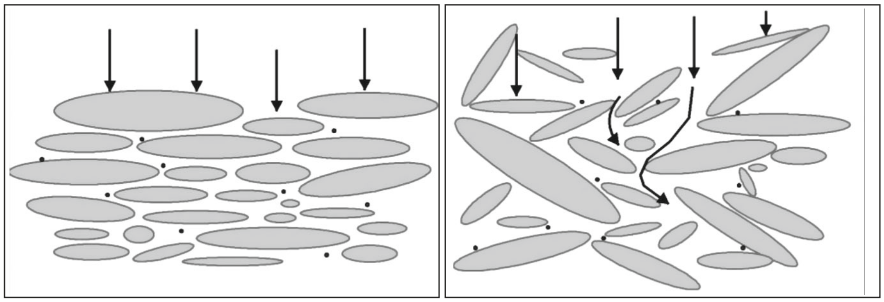

Fig. 4. Sketch of microscopic view of natural (left) and re-packed (right) sediments fabrication.

the original sedimentary structure is completely changed, and the particle arrangement is random (see the right site in Fig. 4). That disturbance will increase the pore space and provide shorter inter-connected pathways for the downward movement of water, which could result in the larger K_{lab} value over K_v value. However, the behavior of sediments also depends on the particle shape, size and surrounding environments, which may lead to different observational findings.

Suitability of Empirical Coefficients in Grain Size Analysis

Song et al. [20] developed a new set of empirical coefficients for eight study sites in the Elkhorn River of Nebraska, so they can be used to calculate approximate K_v values. After applying Song's empirical coefficients, the values are found to be unsuitable for the Platte River. According to Song et al. [20], Kozeny and Hazen equations would tend to overestimate K_v value, while USBR and Shepherd's results were relatively close to in-situ measured K_v. For this study, Shepherd's result differs largely with the K_v value and K_v values are likely agree with Beyer, USBR, and Hazen method. After adopting new C values for the Clarks, Silver Creek, and Duncan sites, the modified K_g values determined by seven empirical methods (Shepherd is not included) present strong agreement with K_v values. The average estimation difference between K_v and K_g is less than 6.25% for each site. The different results between the Elkhorn and Platter River sites suggested that the applicable empirical coefficients to estimate K_v values could vary among different geological and watershed settings.

Particle Size Distribution

Correlation analysis reveals that the connection between grain size derived hydraulic conductivity (K_g) and spectral reflectance (REF) in the channel sediments is observable. REF generally decreases as K_g increases. The reverse relationship could be interpreted by the particle size distribution. The weight percentages of sediments are plotted for particles with size larger than 2 mm and less than 0.25 mm with REF (Fig. 5). As the weight percentage of large particles (>2 mm) increases, REF decreases. In contrast, when the weight percentage of fine particle size (<0.25 mm) rises, REF increases. It is speculated that particle size distribution has a direct influence on both spectral reflectance and hydraulic conductivity determination. Sediments with a larger portion of granules and coarse sand tend to form a rougher surface than sediments consisting mostly of fine sand and silt/clay. This leads to a more scattered reflectance plane for the spectral instrument to catch and lower REF value. In a similar way, sediment samples with larger diameter particle tend to have larger pore size and thus higher infiltration rate (K). Leveraged on the link of particle size distribution between K_g and REF, four linear models are proved to be acceptable to predict non-oriented hydraulic conductivity for fluvial sediments. With available site-specific empirical coefficients, the predicted K values could be further revised to estimate K_v values. The pilot application uses dried streambed sediments and proximal sensing. The study could be further explored by integrating remote-sensing images for predicting hydraulic conductivity values at times when streambeds are completely dry in droughts. The wide coverage of hydraulic conductivities estimations could be extremely meaningful for large-scale groundwater modeling. However, the remote sensing can only detect the top layer of soil surface which may not reflect overall soil or sediment structure, as well as noises caused by soil moisture, crust and vegetation etc. It will also need an accurate calibration facility to eliminate the atmosphere reflection and turbulence; otherwise, the application will generate many uncertainties and errors. Field reflectance measurements may be an intermediate step to overcome the potential deficits.

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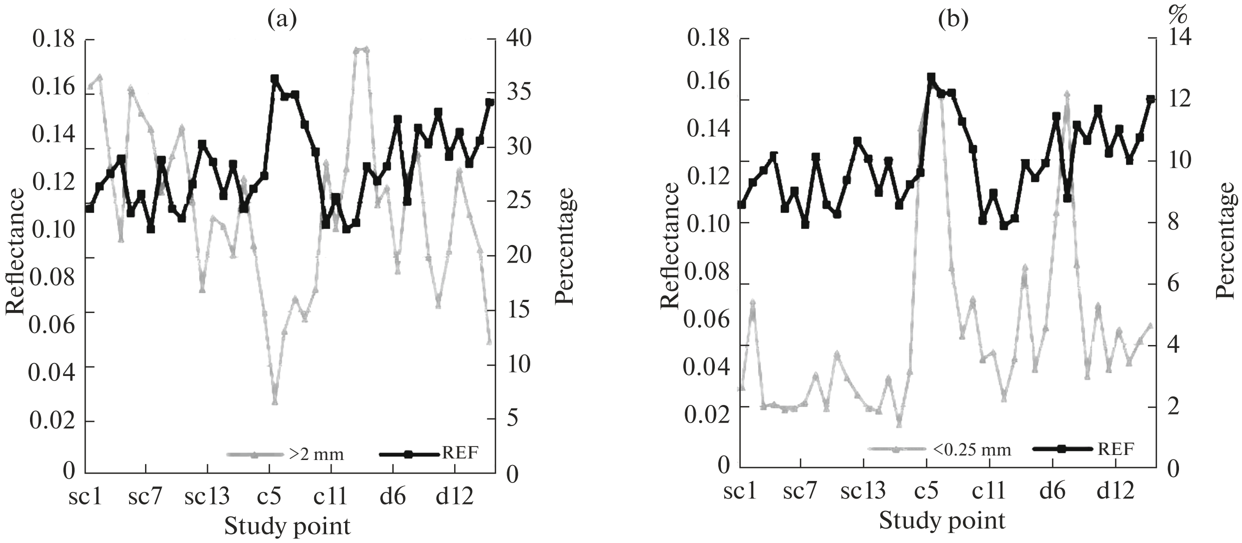

Fig. 5. Plot of weight percentage of coarse (left) and fine sand (right) with reflectance for the Platte River dug-out hole sediments.

spectral process. Finally, many thanks to Xunhong Chen, our deceased mentor, for your life-long supports and encouragements.

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