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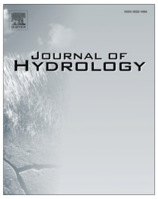

Hydraulic conductivity variation within and between layers of a high floodplain profile

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SUMMARY

We investigated the hydraulic conductivity of a high floodplain of the Weihe River, the largest tributary of the Yellow River in China. We took sediment cores from five layers of the sediments in the high floodplain and performed on-site permeameter tests to determine the horizontal hydraulic conductivity (K_h) of these undisturbed cores. Although the sediments within each layer were relatively homogeneous, the K_h values exhibited variation among the testing locations within each layer. The K_h values from any two layers were statistically different except for the K_h values from layers 1 and 4, which were statistically from the same population. We used the Jarque–Bera and Lilliefors tests to determine the normality of these K_h values. The K_h values from individual layers (layers 1–3) showed normal distribution. When the K_h values from the three layers were combined as a single data set, both statistical tests failed to confirm the normality; instead, the two test methods suggested log-normal distribution. When the K_h values from the five layers were combined as one data set, they also showed a log-normal distribution. These results suggest that hydraulic conductivity values from an individual layer were likely in normal distribution, although their mean and standard deviation varied for individual layers. We then generated random K_h values of normal distribution based on the mean and standard deviation of the field measurements in the five layers, as well as using modified means and standard deviations. When these normally distributed K_h values were combined into one data set for normality analysis, they became log-normal distribution. Clearly, the probability models of hydraulic conductivity depended on how the layout of the measurement locations was placed on porous media consisting of multiple layers of sediments. Hydraulic conductivity from a single layer cannot be simply assumed to be log-normal. The log-normal-distribution model is not always appropriate for characterization of a hydraulic conductivity field for a relatively homogeneous porous medium.

1. Introduction

In the past two decades, numerous researchers have conducted tests in the field for measuring streambed hydraulic conductivities. Some researchers used in situ permeameter tests (Chen, 2000; Landon et al., 2001; Genereux et al., 2008; Dong et al., 2012) or the seepage meter method (Rosenberry and Pitlick, 2009) to determine the vertical hydraulic conductivities; other researchers determined horizontal hydraulic conductivities of streambeds using slug tests (Cardenas and Zlotnik, 2003; Leek et al., 2009), in situ permeameter tests (Ryan and Boufadel, 2007) and on-site permeameter tests (Lu et al., 2012; Cheng et al., 2013). Kelly and Murdoch (2003) proposed a pumping test method in a shallow submerged streambed for estimating the vertical and horizontal hydraulic conductivity of the streambed. Chen (2000) and Cheng et al. (2013) also determined streambed hydraulic conductivity for a desirable direction between horizontal and vertical planes (for example, having a 45° angle from the horizontal direction). Kalbus et al. (2006) published a review paper that listed a variety of methods for determination of streambed hydraulic conductivities. The above studies targeted mainly the submerged streambeds in channels. Several other studies determined hydraulic conductivities of point bars (Nowinski et al., 2011; Dong et al., 2012).

A floodplain is a major part of a fluvial system and represents an important depositional environment. A floodplain is usually exposed above the normal river stage, is under water only during flood events, and receives sediments during these events. In some river valleys, floodplain deposits often are extensive and form a major part of some fluvial aquifers. Generally, a stream channel fill

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consists of coarser materials, compared to its floodplain sediments which consist usually of fine sand, silt and clay (Davis, 1983). Accordingly, hydraulic conductivity in stream channels and in floodplains may exhibit very different ranges and statistical features. However, studies on floodplain hydraulic conductivities have not been carried out as commonly as the studies on the hydraulic conductivity of channel sediments.

Probability distribution models of hydraulic conductivity represent different heterogeneity levels of aquifer permeability. In general, a hydraulic conductivity data set with log-normal probability distribution has stronger heterogeneity compared to a data set that shows normal distribution. The hydraulic conductivity of aquifer materials has commonly been reported to be log-normally distributed in a number of aquifers, for example, the Borden aquifer (Sudicky, 1986) and the Twin Lake aquifer (Killey and Moltyaner, 1988) in Canada, the Cape Cod aquifer in Massachusetts, USA (Hess et al., 1992), the fluvial aquifer in Columbus, Mississippi, USA (Rehfeldt et al., 1992), and the Bejen aquifer in Denmark (Bjerg et al., 1992). Hoeksema and Kitanidis (1985) compiled hydraulic property data sets of aquifers from a number of states in the USA and conducted normality tests. They found that the hydraulic conductivity, as well as the transmissivity and storage coefficients of these aquifers usually had a log-normal distribution. However, a variety of probability distribution models for streambed hydraulic conductivity were reported. Cardenas and Zlotnik (2003) found that the streambed horizontal hydraulic conductivity (K_h) values in Prairie Creek, eastern Nebraska (a tributary of the Platte River), were normally distributed based on 456 measurements. Chen (2005) and Cheng et al. (2011) analyzed streambed vertical hydraulic conductivity (K_v) for 15 study sites in a 250-km segment of the Platte River and found that the K_v values from these 15 sites were normal distribution. A log-normally distributed model for streambed hydraulic conductivity was also reported by Ryan and Boufadel (2007). They conducted falling head permeameter tests to estimate streambed K_h values at two different depths in the Indian Creek in Philadelphia, Pennsylvania. They noted that K_h is log-normally distributed within each sediment layer, but not for the combined dataset of two sediment layers. They reported that streambed K_h decreased with depth while horizontal heterogeneity increased with depth in the two layers. Genereux et al. (2008) carried out in situ permeameter tests to obtain 487 measurements of streambed K_v over the course of a year in West Bear Creek in North Carolina. They found that streambed K_v values were neither normally, nor log-normally distributed, but appeared somewhat bimodal. Springer et al. (1999) suggested a bimodal distribution for the K_h of the sediments within several reattachment bars in the Colorado River in the Grand Canyon, Arizona. The K_h values of Springer et al. (1999) were measured from a group of co-located shallow and deep wells. The shallow and deep wells were positioned across two types of sediment layers, recent flood deposits for the shallow wells and eddy deposits of previous river stages for the deep wells. The above results of studies indicated that probability distribution models of streambed hydraulic conductivity varied from normal, log-normal, to bimodal types, possibly due to sediments being deposited in different depositional conditions. The measurements of hydraulic conductivities in these studies were conducted in stream channels. However, less was known for probability distribution models of K values for other fluvial deposits such as floodplain sediments. It was unclear whether correlations existed between the probability models of streambed hydraulic conductivity and the depositional environment or the number of streambed layers (or lithofacies) investigated. In the analysis of stream–aquifer interactions, researchers (Bruen and Osman, 2004; Kalbus et al., 2009; Ferguson and Bense, 2011; Irvine et al., 2012) assumed that the hydraulic conductivity field for streambeds or for the sediments below the streambed had log-normal distribution in their stream–aquifer models. After studying an alluvial system, Fogg et al. (1998) indicated that hydraulic conductivity should not be assumed to be log-normally distributed, except perhaps within each facies. Thus, the probability distribution of hydraulic conductivity of porous media may be dependent on the scale of the aquifer where the tests for K values were conducted. It is not conclusive that the hydraulic conductivity of the streambed sediments follows a log-normal distribution. Simply assuming a log-normal-distribution hydraulic conductivity field for a relatively homogeneous hydrogeological unit may overestimate the heterogeneity level of the porous medium and can lead to erroneous results of groundwater flow and transport modeling.

The objective of this study was to determine the hydraulic conductivity of a high floodplain which consists mostly of the mixture of reworked loess and sands and to determine the probability distribution models of the hydraulic conductivity in this floodplain. The study area is in a floodplain of the Weihe River. The Weihe River, located in China's central to western parts, is the largest tributary of the Yellow River in China. The river is vital to the economic development of Shannxi Province where the climate condition is arid to semi-arid. We chose this high floodplain because its sediment layers were exposed in an outcrop for easy examination of sedimentary structures. We hypothesized that K values from individual layers of sediments and from multiple layers of sediments may have different probability models. This is because individual layers have relatively uniform grain size and simple sedimentary textures and their K values will have a small variation; in contrast, sediments from multiple layers have wider variations in grain size and complex texture and their K values can vary by several orders of magnitude.

2. Basic hydrology of the Weihe River in the study area

The Weihe River originates from China's Gansu Province, flows eastward through Shannxi Province and merges the Yellow River in the east of Shannxi Province. The total length of the Weihe River is 818 km and its drainage area is 1.36×10^5 km^2. Within Shannxi Province, the Weihe River, flowing through the Guanzhong Plain, is about 320 km long (see Fig. 1). On the north side of the Weihe River in the Guanzhong Plain, several long tributaries flowing through the vast Loess Plateau join the Weihe River. These tributaries bring an enormous amount of reworked loess to the Weihe River. For example, the annual erosion rate in some areas of the Loess Plateau is as high as 5997 ton/km^2 (Jiao et al., 2004). The study results of Qiao et al. (2006) for a site in Gansu Province, the upstream area of the Weihe River, indicated that the average particle size of loess is from 6.8 to 11 μm.

On the south side, numerous tributaries originate from the high and well-vegetated Qinling Mountain. These tributaries are short in length, compared to the tributaries on the north side of the river, have swift flows and carry sand and gravel or cobbles to the Weihe River (Lv et al., 2004). The sediments from the tributaries on the north and south sides of the river are very different, loess and fine particles from the north and coarse materials from the south. Our study site is located near the city of Xianyang (Fig. 1). The sediments of the floodplain consist of yellowish sand, silt and clay.

In the study area, the annual precipitation is about 550 mm. According to Tian (2006), the average annual discharge rate of the Weihe River at the Huaxian stream gauge from 1970 to 2004 was 5.3×10^9 m^3. Most of the discharge occurs from May to October (4.5×10^9 m^3). The river has a low flow period from November to April. The Guanzhong Plain is populous and the average annual water supply per capita is only 386 m^3; thus, water scarcity is a serious problem (Shang, 2007). Industrial development and population growth in the past several decades produced a large