Study on variation rule of permeability coefficient in unsaturated zone along the WeiHe River in the intertidal area

Nan Zhang 1, *, Lin Li 2, Hong Jiang 3, Huijuan Yin 1, Xiaohui Su 1

1 Yellow River Institute of Hydraulic Research, Zhengzhou, China
2 North China University of Water Resources and Electric Power, Zhengzhou, China
3 Yellow River Basin Water Resources Protection Bureau, Zhengzhou, China

*Corresponding author e-mail: zhangnan19810202@126.com

Abstract. As a collection place of surface runoff, river is the main place for the water exchange and water quality. It is importance to analyse the interaction between groundwater and surface runoff for the spatial variation of permeability coefficient. In this paper, the unsaturated zone in the intertidal area of WeiHe river basin was taken as the research area. The spatial distribution of vertical permeability coefficient was analysed by histogram statistical test. We analysed the function relation between the variance and correlation length of the numerical value and the macroscopic dispersion of sediment. The results show that the average vertical saturated permeability coefficient of unsaturated zone is 0.012 cm/s, the variation of permeability coefficient has strong spatial variability. The vertical permeability coefficient of the unsaturated zone along the WeiHe in the intertidal area with the logarithmic normal distribution rule. The longitudinal macroscopic dispersion of the unsaturated zone is 9.7m, and longitudinal macroscopic dispersion is related to the research scale.

1. Introduction

With the development of society and the improvement of people's living standard, the influence of pollution on surface water and groundwater becomes increasingly serious. The sediment in the river bed and its intertidal area connects the surface water with the groundwater system. The infiltration coefficient directly affects the water supply to the surrounding groundwater and the groundwater excretion to the river (Shu Longcang,2002). The spatial distribution of permeability coefficient is an important factor affecting the migration and spatial distribution of solute in groundwater system (Han Zaisheng,1989). Macroscopic dispersion refers to the dispersion phenomenon observed in heterogeneous aquifers, and its corresponding parameter is called macroscopic dispersion. In the simulation of solute migration in sediment, macroscopic dispersion is more important than that in the void scale, which directly affects the movement and diffusion of solute in the aquifer. The permeability of river sediment and macroscopic dispersion degree affects the river to the aquifer of infiltration and the excretion of the aquifer to the river, which has an important influence for the river-hydraulic connection strength of groundwater and solute transport.

At present, there are few systematic studies on the key hydrogeological parameters such as the river sediment permeability coefficient and macroscopic dispersion. Therefore, this study select four river segment(xianyang, xi'an,Lintong, Huaxian) in the WeiHe river as the research area, which to research
the permeability coefficient and the spatial variability. First, in order to provide more theoretical basis for the Weihe river restoration of the ecological environment, this research can compensate for the inadequacy of river spatial hydrogeological parameter variability study in theory. Second, provide detailed data support for the actual application to groundwater solute transport model, provide scientific basis for the monitor and control the spread of pollution in rivers and groundwater quality system, to improve the quality of domestic production water coastal cities. Third, promote the river-the implementation of the integrated water resources management of groundwater.

2. Materials and methods

2.1. Study area and Test points

The Weihe River is a vital river of Shaanxi Province, China, belongs to arid and semi-arid regions in western China, which is the largest tributary of the Yellow River. The total basin area is 134,000 km². The Weihe river basin in Shaanxi province is mainly the middle and lower reaches of Weihe river area. The Weihe River influences the vicissitude of social and economy in Shaanxi Province directly (Song, 2013). The research of the spatial variability of streambed Kv value of the Weihe River is significantly important to analyze the health of the river system.

Based on field investigation and data collection of Weihe river in Shanxi Province analysis, finally choose the middle and lower reaches of Weihe river in Xianyang, and Xi 'an, Lintong, Huaxian four county typical study area (Fig 1, Table 1). The test point distribution is shown in figure 2.

![Fig. 1 Map of study area and tests sites](image)

**Table 1.** Average stream discharge and stream level in four gauges stations

| Station location | Longitude and Latitude | Mean stream discharge (m³/s) | Mean stream level (m) | Date range |
|------------------|------------------------|------------------------------|-----------------------|------------|
| A                | 107.05, 34.38          | 85                           | 493                   | 2004–2016  |
| B                | 107.7, 34.30           | 158                          | 382                   | 2004–2016  |
| C                | 108.7, 34.32           | 234                          | 352                   | 2004–2016  |
| D                | 109.77, 34.58          | 257                          | 336                   | 2004–2016  |
2.2. Methods

We apply an in-situ permeability coefficient test, using the falling head method by inserting transparent polycarbonate standpipes into sediments (Fig. 3). The pipes, staked vertically into the streambed sediments, are 160 cm in length, 1-mm thick and 6 cm in diameter. After being pressed into a desired depth, the pipe was kept in the streambed for an appropriate time in order to allow the hydraulic head inside the tube to reach equilibrium to attune to the compaction of the streambed sediments inside the pipe (Chen, 2009). As the hydraulic head in the tube falls, the head was recorded in different time. In this study, water levels were recorded more than 5 times for each permeability coefficient test. Any group of data from the in-situ permeability coefficient tests can be used to calculate the Kv value using the equation of Hvorslev (1951):

\[ k_v = \frac{\pi D}{11m} \ln\left(\frac{h_1}{h_2}\right) \]  

(1)

\[ m = \sqrt{\frac{k_h}{k_v}} \]  

(2)

Where \( L_v \) is the length of sediment in the tube; \( h_1 \) and \( h_2 \) are hydraulic head inside the pipe measured at times of \( t_1 \) and \( t_2 \), \( D \) is the inner diameter of the pipe, \( K_h \) is the horizontal hydraulic conductivity of the streambed sediment around the base of the sediment core.

2.3. Dispersion analysis method

Dispersion mainly describes the diffusion of solute in porous media caused by hydrodynamic dispersion and molecular diffusion. Hydrodynamic dispersion role mainly in the heterogeneity of single pore channels flows with large range of time and space caused by local heterogeneity of heterogeneous aquifers, and caused by heterogeneity dispersion effect is known as macroscopic dispersion.

The dispersion degree(\( \alpha \)) is used to describe the diffusion degree of solute deviating from water quality point in the process of groundwater system migration. Yang Jinzhong (1997) assumed that
unsaturated permeability coefficient and absorption coefficient are in conformity with the second-order stationary gaussian random function, when the unsaturated water movement of the main force of gravity, it is concluded that macroscopic dispersion degree \( A_{zz} \) expression.

\[
A_{zz} = A_{z1} + A_{z2} + A_{z3}
\]

When the migration distance of solute is relatively short, that is, \( Zc/\lambda f << 1 \) and the adsorption coefficient \( Kd \) is linearly related to the permeability coefficient \( Ks \),

\[
A_{zz} = \left\{ \exp (\sigma_2 f + H^2 \sigma_\alpha^2) - 1 \right\} \cdot 2 \cdot \left( 1 - \frac{1}{<R>} \right) \cdot \left\{ \exp (\beta \sigma_2 f) - 1 \right\} + \left( 1 - \frac{1}{2} \cdot <R> \right) \cdot \left\{ \exp (\beta^2 \sigma_2 f) - 1 \right\} \cdot Zc
\]

When the migration distance of solute is relatively short, that is, \( Zc/\lambda f << 1 \) and the adsorption coefficient \( Kd \) is linearly unrelated to the permeability coefficient \( Ks \):

\[
A_{zz} = \left\{ \exp (\sigma_2 f + H^2 \sigma_\alpha^2) - 1 \right\} \cdot \left( 1 - 1/2 <R> \right) \cdot \left\{ \exp (\sigma_2 d) - 1 \right\} \cdot Zc
\]

\( Zc \) is the average transport distance of solute; \( \sigma_2 f, \sigma_2 \alpha, \sigma_2 d \) is the variance of natural ln (\( Ks \)), unsaturated soil parameters \( \alpha \) and natural ln (\( Kd \)), \( <R> \) is adsorption factor; \( \beta \) is constant; \( \rho \) is the bulk density of the soil; \( H \) is the average pressure head; \( E(\ast) \) is the exponential integral; \( \gamma \) is the Euler constant, value is 0.577.

In this paper, there are exist two hypotheses in calculating the permeability coefficient. One is to consider only the permeability coefficient on the plane, the other is to consider that the X-axis of the study area is parallel to the direction of the river, \( \gamma = 1 \). That is, the calculation formula of longitudinal macroscopic dispersion in this paper is:

\[
A_{L} = \frac{\sigma_f^2}{\lambda}
\]

3. Results and Analyses
In this paper, four typical intertidal areas (xianyang, xi’ an, lintong and huaxian) of the Weihe river basin, Shaanxi province, which was taken as study areas respectively.

The permeability coefficient of the unsaturated zone in the intertidal zone of the study area is shown in the table. It can be seen that the calculation results of the permeability coefficient range from 10-4~0.07 cm/s, with a large difference in size. The total mean value is 0.012 cm/s, and the total standard deviation is 0.014 cm/s.

Each row of data analysis in the direction along the river can be seen (Table 2), there are some difference between average \( K_v \) value and mid-value in each row. In comparison, the top 10 difference slightly larger, slightly smaller differences in the back, and each row of \( K_v \) value of standard deviation and average \( K_v \) value was basically at the same order of magnitude, so it could reflect that each row of data is difference.

According to the data analysis results along the WeiHe River in the intertidal area, which perpendicular to the direction of the river each row, we can see that(Table 3), each column \( K_v \) value difference is bigger between average value and mid-value, deviation is smaller than each column \( K_v \) value of average value and mid-value. This reflect that the variability of permeability coefficient in vertical is smaller than the horizontal. The variance and average value of \( K_v \) are also in the same order of magnitude, indicating that the distribution of \( K_v \) value is very different in the vertical distribution.
| Number | \( K_v \) (cm/s) (average) | \( K_v \) (cm/s) (mid-value) | \( K_v \) (cm/s) (standard deviation) |
|--------|-----------------------------|-----------------------------|----------------------------------|
| 1      | 0.0125                      | 0.0055                      | 0.0164                           |
| 2      | 0.0178                      | 0.0124                      | 0.0165                           |
| 3      | 0.0164                      | 0.0067                      | 0.0182                           |
| 4      | 0.166                       | 0.0127                      | 0.0151                           |
| 5      | 0.0145                      | 0.0054                      | 0.0166                           |
| 6      | 0.0131                      | 0.0045                      | 0.0144                           |
| 7      | 0.0119                      | 0.0047                      | 0.0134                           |
| 8      | 0.0153                      | 0.0057                      | 0.0212                           |
| 9      | 0.011                       | 0.0049                      | 0.0117                           |
| 10     | 0.0107                      | 0.0043                      | 0.0112                           |
| 11     | 0.015                       | 0.0076                      | 0.0191                           |
| 12     | 0.0105                      | 0.0053                      | 0.0128                           |
| 13     | 0.0086                      | 0.0052                      | 0.0092                           |
| 14     | 0.0079                      | 0.0062                      | 0.0071                           |
| 15     | 0.0072                      | 0.0047                      | 0.0081                           |
| 16     | 0.0053                      | 0.0029                      | 0.0069                           |
| 17     | 0.0085                      | 0.0043                      | 0.0091                           |
| 18     | 0.0081                      | 0.0065                      | 0.0067                           |
| 19     | 0.0096                      | 0.0053                      | 0.0116                           |
| 20     | 0.0118                      | 0.0063                      | 0.0139                           |
| 21     | 0.0095                      | 0.0055                      | 0.0097                           |
| 22     | 0.0099                      | 0.0039                      | 0.0116                           |
| 23     | 0.0068                      | 0.0043                      | 0.0065                           |
| 24     | 0.0163                      | 0.0077                      | 0.0211                           |
| 25     | 0.0111                      | 0.0061                      | 0.0104                           |
| 26     | 0.0115                      | 0.0078                      | 0.0109                           |
| 27     | 0.0172                      | 0.0125                      | 0.0163                           |
| 28     | 0.020                       | 0.013                       | 0.0197                           |

Table 3. \( K_v \) values of each column in the unsaturated zone

| Number | \( K_v \) (cm/s) (average) | \( K_v \) (cm/s) (mid-value) | \( K_v \) (cm/s) (standard deviation) |
|--------|-----------------------------|-----------------------------|----------------------------------|
| 1      | 0.0056                      | 0.0038                      | 0.0096                           |
| 2      | 0.0067                      | 0.0039                      | 0.0077                           |
| 3      | 0.0041                      | 0.0039                      | 0.0026                           |
| 4      | 0.0044                      | 0.0033                      | 0.0029                           |
| 5      | 0.0102                      | 0.004                       | 0.017                            |
| 6      | 0.0082                      | 0.0048                      | 0.0116                           |
| 7      | 0.0081                      | 0.0059                      | 0.0068                           |
| 8      | 0.0062                      | 0.0039                      | 0.0072                           |
| 9      | 0.0071                      | 0.0049                      | 0.0084                           |
| 10     | 0.0068                      | 0.0053                      | 0.0051                           |
| 11     | 0.0073                      | 0.0029                      | 0.0094                           |
| 12     | 0.0095                      | 0.0046                      | 0.0109                           |
| 13     | 0.0131                      | 0.0068                      | 0.0157                           |
| 14     | 0.0107                      | 0.0112                      | 0.0155                           |
| 15     | 0.0063                      | 0.0034                      | 0.0068                           |
| 16     | 0.0153                      | 0.0056                      | 0.0235                           |
| 17     | 0.0082                      | 0.0044                      | 0.0101                           |
| 18     | 0.0054                      | 0.0031                      | 0.0064                           |
| 19     | 0.007                       | 0.0032                      | 0.0077                           |
| 20     | 0.0193                      | 0.019                       | 0.0152                           |
| 21     | 0.0203                      | 0.0189                      | 0.0154                           |
| 22     | 0.0215                      | 0.0178                      | 0.0146                           |
| 23     | 0.0197                      | 0.0182                      | 0.0139                           |
| 24     | 0.0196                      | 0.0212                      | 0.0115                           |
| 25     | 0.0138                      | 0.0075                      | 0.0198                           |
| 26     | 0.0189                      | 0.017                       | 0.0161                           |
| 27     | 0.0168                      | 0.0097                      | 0.0117                           |
| 28     | 0.0161                      | 0.0145                      | 0.0125                           |
Therefore, the data in table 2 and table 3 show that the permeability coefficient of the unsaturated zone sediment has strong spatial variability whether it is parallel to or perpendicular to the channel.

Seen from the determination permeability coefficient (Kv) of saturated and unsaturated zone in the studied area, saturated with Kv value is larger than unsaturated zone. In Shaanxi province, the source of the sediments are mainly in the south of the Weihe river in the north of qinling mountains and loess tableland, qinling mainly import mainly particles coarser grit sediment, the loess tableland import is given priority to with silty sediment and argillaceous sediment. Due to the large change of rainfall season in the Weihe river basin, the water level of Weihe river is very different in each season. Therefore cause sediment composition is complicated in Weihe river, and the change of sedimentary facies is very big, this is the reason that makes the sediment of hydrogeological parameters, such as the coefficient of permeability have a strong spatial variability.

The Kv data and lnKv data of unsaturated zone measurement points were tested and analyzed respectively, and the histogram was obtained as shown in the figure below. It can be seen that the logarithmic normal histogram and fitting graph of unsaturated zone permeability coefficient Kv have good effects. Therefore, as a whole, the spatial permeability coefficient of unsaturated zone in Weihe intertidal area conforms to the logarithmic normal distribution rule. In order to better determine the distribution rule of Kv in unsaturated zone, statistical test and analysis were carried out for each row of test data, some representative samples were selected for analysis parallel to and perpendicular to the river section.

![Kv histogram and fitting diagram](image1)

**Fig.4** Kv histogram and fitting diagram

![Logarithmic histogram and fitting graph of Kv](image2)

**Fig.5** Logarithmic histogram and fitting graph of Kv

It can be seen that the logarithmic normal histogram of the infiltration coefficient Kv in the unsaturated zone in the study area has a good effect, and the logarithmic normal state fitting diagram shows that the logarithmic normal state fitting effect of Kv is better. Therefore, on the whole, the saturated spatial permeability coefficient of the unsaturated zone in the intertidal zone of Weihe river basin also conforms to the logarithmic normal distribution rule.
In order to determine the \( K_v \) distribution of intertidal area zone, also statistical test for each row of data to analyze, choose the representative of each row (parallel to the river), and each column (perpendicular to the river) is analyzed.

![Fig.6 Row 10 \( K_v \) logarithmic histogram and fitting graph of unsaturated zone](image)

![Fig.7 Row 14 \( K_v \) logarithmic histogram and fitting graph of unsaturated zone](image)

Above you can see that, parallel to and perpendicular to the rivers \( K_v \) value of the coefficient of permeability of unsaturated zone of lognormal testing effect is good. This could represent on spatial distribution rule of permeability coefficient in Weihe intertidal area in the Shaanxi province. It can be seen that the permeability coefficient of lognormal fitting better parallel to the river more than perpendicular along the river. Indicate that the effect the rule of normal logarithmic, which is the permeability coefficient of unsaturated zone in the direction parallel along the river is better than perpendicular to the river.

In this paper, the maximum longitudinal macroscopic dispersion value of the unsaturated zone in the intertidal zone of Weihe river basin in Shaanxi province is 9.7m by using the macroscopic dispersion calculation formula. The calculation results of each row are shown in table 6:

| Parameter | Total | 20*20 | Row 7 | Row 10 | Row 14 |
|-----------|-------|-------|-------|--------|--------|
| \( \sigma^2 \) | 1.3068 | 0.9313 | 1.526 | 1.145 | 1.1557 |
| \( \lambda \) | 7.42 | 6.24 | 3.04 | 1.85 | 2.51 |
| \( A_L(m) \) | 9.7 | 5.81 | 4.64 | 2.12 | 2.9 |

You can see that the unsaturated zone as a total data of longitudinal macroscopic dispersion degree is bigger, when the scale reduce to 20*20 sampling point area, longitudinal area is smaller than the total
macroscopic dispersion degree, longitudinal macroscopic dispersion degree value is greater than the row. When the data of each row is analyzed, the longitudinal macroscopic dispersion values of each row are not much different.

Related studies have shown that (Huang), hydrodynamic dispersion of porous media is a scale effect, due to the heterogeneity of the wild medium characteristics as the research scale increases, so as to make the field experiment to obtain the dispersion degree of value also increases with the increase of research scale. However, when the research scale is increased to a certain range, the dispersion value tends to be a stable value, and no major changes will occur. At this point, the dispersion value is the maximum value in the research area. Therefore, when the correlation length of the spatial variation of sediment permeability coefficient is different, the longitudinal macroscopic dispersion degree is different. When the regional scale heterogeneity cannot reflect the statistical characteristics of the whole study area, the calculated macroscopic dispersion value will be relatively small. Therefore, the longitudinal macroscopic dispersion values calculated in this paper also have some differences in size.

4. Conclusion
1. Standpipe method calculating the average vertical saturated permeability coefficient of unsaturated zone is 0.012 cm/s, the change of permeability coefficient is larger, have very strong spatial variability.
2. The vertical permeability coefficient in unsaturated zone along the Weihe intertidal conform to the logarithmic normal spatial distribution rule.
3. The vertical macroscopic dispersion value of sediments in Weihe intertidal area is directly deduced according to the functional relationship between the variance of the permeability coefficient and the correlation length. The total longitudinal macroscopic dispersion of the unsaturated zone is 9.7m, and the longitudinal macroscopic dispersion is related to the research scale.

Acknowledgments
This research was financially supported by National key research and development plan No.2017YFC0403505 and Central public welfare research institutes basic scientific research business expenses special funds HKY-JBYW-2016-25 and the research of National Natural Science Foundation of China(NSFC) No.51309107. We also thankful to anonymous reviewer for his constructive comments in the manuscript review.

References
[1] Su Longcang, CHEN Xun-hong,. Measurement in situ of streambed hydraulic conductivities in the Platte River, Nebraska[J]. Advances in water science, 2002, 13(5):629-633.DOI: 10.14042/j.cnki.32.1309.2002.05.017. (in Chinese)
[2] Han Zaisheng. Macroscopic dispersion in vertical heterogeneous aquifers [J]. Engineering investigation, 1989, 6:27-30. (in Chinese)
[3] Chen XH, Song J, Cheng C et al., 2009. A new method for mapping variability in vertical seepage flux in streambeds. Hydrogeol Journal, 17(3):519-525. DOI: 10.1007/s10040-008-0384-0.
[4] Hvorslev, M. J, 1951. Time lag and soil permeability in ground-water observations.U.S. Army Corps of Engineers, Waterways Experiment Station Bulletin, 36: 1-50.
[5] Chen X.H. Statistical and geostatistical features of streambed hydraulic conductivities in the Platte River, Nebraska[J]. Environmental Geology, 2005, 48(6): 693-701.
[6] Yang Jinzhong, Cai Shuying, Ye Zitong. An Analysis fo Macrodispersivity for Adsorbing solute transport in heterogeneous unsaturated soils.[J].Journal of Hydrodynamics, 1997, 12(4): 407-413.DOI:10.16076/j.cnki.cjhd.1997.04.005.
[7] Huang K.L. Progresses and prospect on field-scale dispersion in porous media aquifers[J]. Hydrogeology and Engineering Geology,1991, 18 (3/4):30-33.
[8] Zhang Bo, Song Jinxil, Cao Mingming, 2013. Effect of sediment particle composition on vertical hydraulic conductivity of Weihe River streambed. Bulletin of soil and water conservation, 33(5): 40-44. (in Chinese)