



# Influence of hydraulic gradient and temperature on the migration of *E. coli* in saturated porous media during bank filtration: a case study at the Second Songhua River, Songyuan, Northeastern China

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**Abstract** River bank filtration can effectively reduce the number of pathogenic microorganisms infiltrating into groundwater from surface water. Groundwater seepage velocity and temperature are considered to be important factors affecting the process, but the magnitude and mechanism of their impacts have not been clear for a long time. Based on the actual monitoring data of the *Escherichia coli* concentrations and soil samples of Second Songhua riverside source area, the migration of *E. coli* in saturated porous media under different velocities and different temperatures was studied using saturated soil column transport experiments. Concurrently, the migration characteristics of *E. coli* in the riverside source area were replicated by mathematical simulation. According to the field monitoring results, the concentration of *E. coli* decreased in the riverbank infiltration zone, and the removal rate was greater than

96%. The column experimental results showed that the lower the flow velocity was and the higher the temperature was, the greater the removal rate of *E. coli* was. And the flow velocity was the main factor affecting the removal of *E. coli*. The mathematical simulation results showed that under the conditions of the largest hydraulic gradient (20%) and the highest concentration of *E. coli* (2500 MPN/100 mL) in river water, the safe exploitation distance of groundwater that did not cause a risk of *E. coli* pollution was more than 7 m away from the river bank. These findings are expected to provide a scientific basis for the design of water intake schemes and the optimization of mining technology.

**Keywords** *Escherichia coli* migration · Temperature · Hydraulic gradient · River water infiltration

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## Introduction

River bank filtration (RBF) process has been widely proven to be a highly efficient and low-cost treatment technology (or pretreatment technology) to remove natural organic matter, turbidity, pesticides, pigments and other organic pollutants in surface water (Ray et al. 2002; Verstraeten et al. 2002; Sharma et al. 2012). Approximately 75%, 80%, 50% and 45% of the drinking water in Berlin, Switzerland, Slovakia and Hungary depend on RBF (Kuehn and Mueller 2000; Massmann et al. 2008; Grischek et al. 2002). Since the early 1950s, a number of riverside water sources have been established in northern China and there are more than 300 large riverside water sources in China nowadays (Wang et al. 2016; Hu et al. 2016). At present, there have been many studies on water exchange and water quality evolution in riverside water sources (Schubert 2002; Teng et al. 2018; Zhu et al. 2019).

However, microbial contamination of surface water becomes increasingly serious. Microbe-contaminated river water will inevitably pose a serious threat to the groundwater quality during the RBF processes. According to the World Health Organization (WHO) guidelines for drinking water quality (World Health Organization 2011), most of the health problems related to drinking water arise from contamination by microorganisms (bacteria, viruses, protozoa or other biological sources). These microbes are generally derived from the excrement of humans and animals, and they generally exhibit strong resistance to the environment and can survive for several days or even months in nature (John and Rose 2005). Stagnant wastewater bodies, livestock operations, land applications of sewage, sanitary landfills and leaking on-site wastewater treatment systems such as septic tanks also introduce microorganisms into subsurface water bodies (Łuczkiwicz 2007). As a result, the concentration of viruses and other pathogens may be particularly high, which poses a great challenge to drinking water treatment (Da Silva et al. 2011; Ashbolt 2004; Lutterodt et al. 2012). In the development and utilization of water resources, microbial indicators are of great significance to the evaluation of water quality. *Escherichia coli*, a bacterium inhabiting the intestines of animals, is often dispersed in the environment with feces. Because of its rapid and

convenient detection, *E. coli* has become an important indicator of fecal pollution.

The available research results show that the RBF process has a good removal effect on microorganisms such as *E. coli*, *Giardia* and *Cryptosporidium*, and the removal rate can be as high as 99% (Weiss et al. 2005; Tufenkji et al. 2002; Thakur et al. 2013; Gupta et al. 2009). Under natural conditions, both the properties of porous media and the groundwater occurrence condition will have significant impacts on the transport of *E. coli*. Simultaneously, *E. coli* is a bio-colloid, and the factors affecting its life activities may also change the migration process. Many factors such as cell type, medium particle size, pore water velocity, moisture content, pH, ionic strength and surface roughness have been studied during *E. coli* migration (Chen and Walker 2012; Bai et al. 2016; Zhong et al. 2017).

Unlike other pollutants, *E. coli* is a biological pollutant whose activity is closely related to temperature. Therefore, the influence of temperature on the transport of *E. coli* in aqueous medium cannot be ignored. In particular in the high latitudes and cold regions of Northeast China, the climate is cold and dry in winter and hot and rainy in summer. Temperature changes under natural conditions have an important impact on the growth and migration of *E. coli*. At the same time, temperature is the key parameter to characterize the adsorption kinetics and thermodynamic characteristics. Based on the available research results, temperature affects bacterial adsorption and transport in porous media due to temperature-induced changes in fluid viscosity (Stevik et al. 2004), conductivity (Gharabaghi et al. 2015), cell surface hydrophobicity (Gallardomoreno et al. 2003) and the conformation of extracellular polymer on the bacterial surface (Kim and Walker 2009). However, great uncertainty persists concerning whether elevated temperatures will promote or inhibit bacterial transport in porous media (Chrysikopoulos and Aravantinou 2014; Gharabaghi et al. 2015; Sasidharan et al. 2017; Jiang et al. 2007).

In the past, most experimental studies on bacterial transport have utilized a given particle size material (high-purity quartz sand was chosen in most cases) (Sasidharan et al. 2017). As demonstrated by the research of Regli et al. (2003) and Frind et al. (2006), controlled conditions in laboratory studies are unable to reproduce the natural heterogeneity of environmental sites, which is a decisive factor in determining

potential hazards for drinking water extraction wells. The use of natural soil media to conduct research will provide more practical guidance on bacterial removal and pollution control.

Furthermore, for RBF technology, the natural fluctuation of the water level and the change in the mining intensity have led to different flow velocities in aquifer media. To reflect the real environmental conditions to the greatest extent possible, this paper focuses on the transport of *E. coli* in saturated porous media during the infiltration of river water under different temperatures and hydraulic gradients through field sample analysis, column experiments and numerical simulation. The study result will be of great significance for the assessment of the risk of microbial contamination in riverside water sources.

## Materials and methods

### Study site

The study area (Fig. 1) is located in the southwest of Ningjiang District (124°42′–124°48′ E, 45°08′–45°11′N), Songyuan, Jilin Province, China, which is approximately 15.3 km<sup>2</sup>. The Second Songhua River flows through the northern part of the study area from southeast to northwest, which is the main surface water source in the region with an annual average runoff of 476 m<sup>3</sup>/s. The topography in the riverside area is relatively flat, and the landform is a river floodplain. The quaternary sand gravel pore water aquifer with a close hydraulic connection with the river water is approximately 18–20 m in thickness. The aquifer media are mainly loose sediments such as sands and gravels. There are 8 water supply wells along the edge of the river (Fig. 1). The depth of each well is 20 m, and the total amount of mining is approximately 9000 m<sup>3</sup>/d. They are important water supply sources for the Songyuan oil field power plant.

Affected by continued exploitation, the groundwater depression cone has been formed in the southeast–northwest direction (Fig. 2a). The annual average recharge of the Second Songhua River to the groundwater reaches 65%. To investigate the temporal and spatial distribution of *E. coli* during river infiltration in the study area, a row of observation wells (wells A–F) at different distances (2 m, 4 m, 6 m, 8 m, 20 m and

50 m) from the river banks were installed. The depth of all the wells was approximately 6.5 m (Fig. 2b).

According to the observed data (Fig. 3), the level of river water was significantly higher than the groundwater, and the water level difference was between 0.5 and 1 m. Concomitantly, the hydraulic gradient was largest in August (19.23%), followed by September (10.57%), while it was smallest in November (the river was frozen and no data were measured). In summer (June–August), the river temperature was approximately 25 °C, while the groundwater temperature was 10–15 °C, which decreased gradually with increasing distance from the river bank. In winter (November–May), the temperature of river water and groundwater was both low: the river water temperature was approximately 4 °C and the groundwater temperature was basically maintained at 6–8 °C.

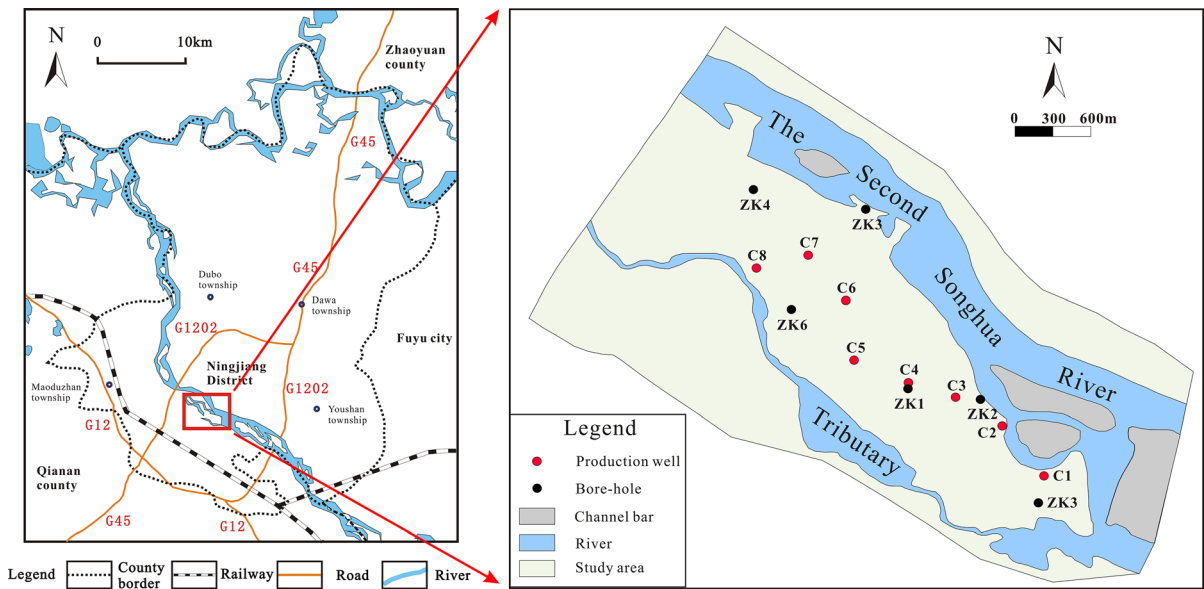
### Sample collection and monitoring

River and groundwater samples were collected in August, September and November 2016. River water samples were obtained directly from the Second Songhua River at a depth of 10–15 cm below the water surface, and groundwater samples were obtained after purging the wells from A to F. All samples were collected in a sealed aseptic bottle placed at 4 °C, and the test was completed within 4 h after sampling.

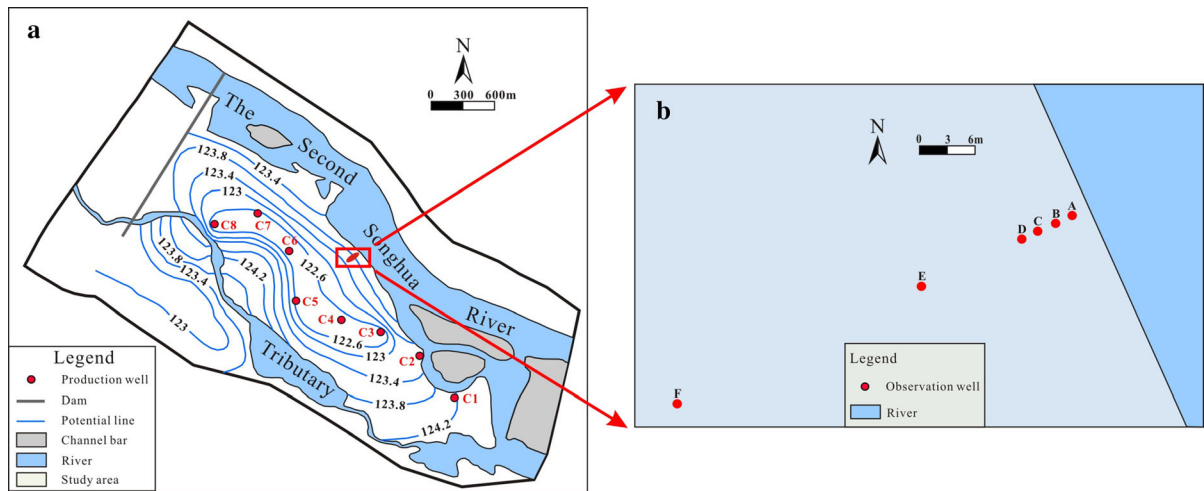
A sediment sampler, type Beaker portable sampler, was used to collect sediment samples from the riverbed, and a ring knife was used to collect the undistributed samples of aquifer sediment (well ZK2, Fig. 1) in December 2015. The particle size distribution of the sediments was analyzed using a Battersize 2000 laser particle size analyzer and screen mesh in the laboratory.

### *E. coli* test

To meet the requirements of convenient and rapid detection, the enzyme–substrate technique was used to test the concentration of *E. coli* in this study (US EPA 1998). The enzyme–substrate method is easy to operate and has a short detection time. The operation process does not need to be performed in a sterile environment, and the most likely number (MPN) value of coliform bacteria and *E. coli* in the water sample can be simultaneously determined in only 18–24 h. The



**Fig. 1** Location of the study area



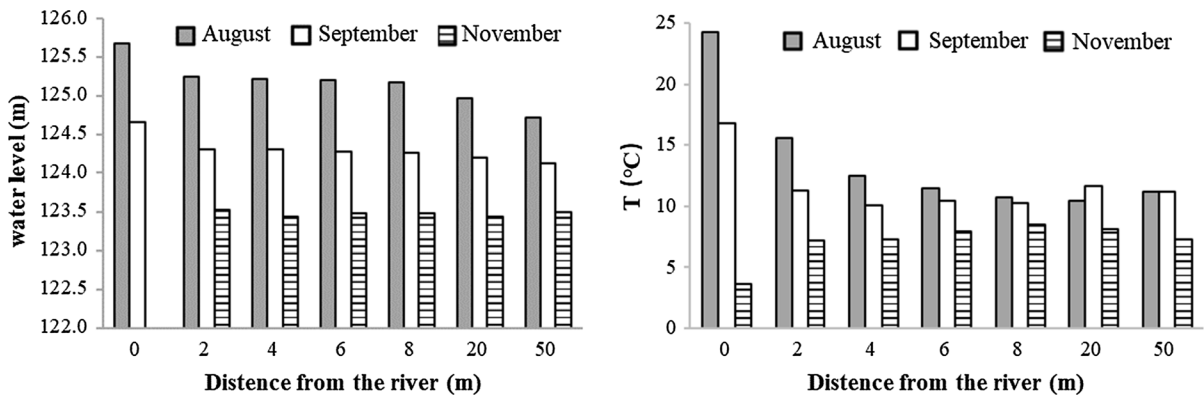
**Fig. 2** Contour lines of groundwater levels and distribution of monitoring stations (November 5, 2015)

accuracy of this method was tested in this study. The results showed that the concentration of *E. coli* was 1119.9 MPN/100 mL for the raw sample and 114.5 MPN/100 mL for the samples diluted 10 times. The test error matched the research accuracy.

**Bacterial preparation**

The *E. coli* (0.5 × 1–3 μm) used in this research were purchased from China General Microbiological

Culture Collection Center in order to ensure the safety of the experimenters. The bacteria were grown in LB liquid culture for 5 h at 37 °C (200 rpm), and all cultures were harvested in stationary phase by centrifugation (1800 rpm, 10 min). The cells were rinsed twice with stroke-physiological saline solution (pH = 7.0) and then resuspended in identical NaCl solution. The concentration of the bacterial solution was controlled at 10,000 MPN/100 mL by the step dilution method during the experiments.



**Fig. 3** Temporal and spatial variation in river water and groundwater level and temperature in river infiltration zone

Column experiment

The experimental schematic is shown in Fig. 4. The inner diameter of the plexiglass column was 5 cm, and the effective height was 50 cm. The porous medium of the site (river bed sediments and aquifers) was used as the packing material for the column experiments. Prior to the experiments, both the porous media and the column were sterilized. According to the natural density of the porous medium in the site, the site size is reduced according to the ratio of 1:20 so that the top 20 cm was filled with loamy sand, the middle 20–40 cm was filled with less gravelly soil, and the bottom 40–50 cm was filled with gravel soil. After the soil column was filled, the average porosity was 0.37, and the hydraulic conductivity of the soil column was 3.52 m/d.

Sampling points were set every 10 cm at the side of the column, and a 200-nylon screen net was used at the bottom outlet and the side sampling hole to avoid sand loss. The glass bottle was filled with injection liquid, and the peristaltic pump was used to control the injection rate. To simulate the underground condition, the columns of plexiglass were wrapped in black plastic bags. First, the column was filled with sterile deionized water from the bottom to the top to achieve the saturated station. When the experiment was initiated, sterile deionized water was injected downward from the inlet of the column until the conductivity at each sampling holes was stable, and then, it was replaced with bacterial solution.

Five soil column experiments were carried out to investigate the transport characteristics of *E. coli* under different temperatures and hydraulic gradients.

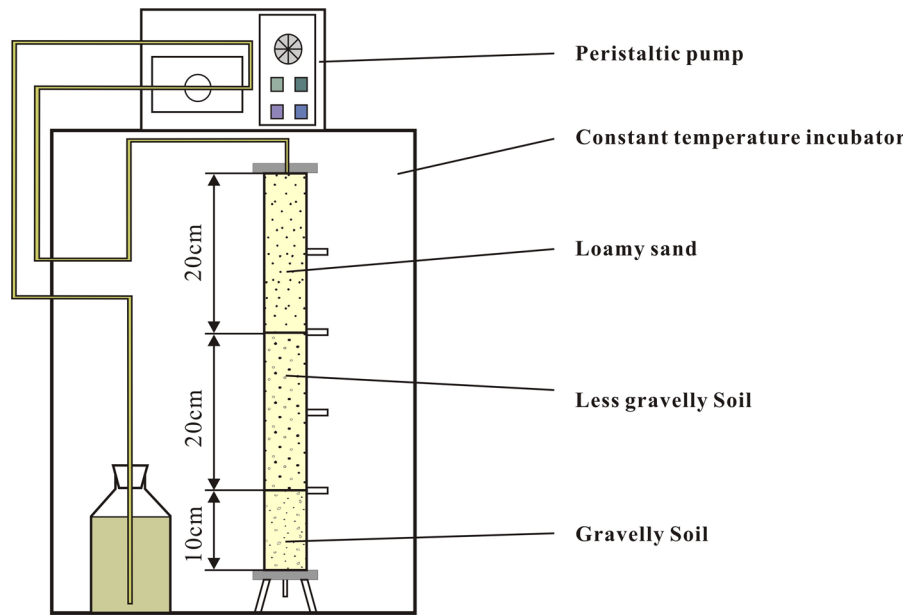
In the experiment, the measured hydraulic gradient (10%, 15%, 20%) was transformed into flow velocities (0.48 mL/min, 0.72 mL/min and 0.96 mL/min). To simulate the real environmental temperature, 25 °C was selected for the inflow temperature and 12 °C for the column temperature to reflect summer conditions, and 4 °C was selected for both the inflow and column temperature to reflect winter conditions. 8 °C was chosen as the inflow and column temperature to reflect spring and autumn conditions. In the Z5 experiment, the glass bottle containing the bacterial solution was placed outside the constant-temperature incubator. The experimental conditions are summarized in Table 1.

After the transport experiments, 12 g medium was collected at the depth of 0 cm, 10 cm, 20 cm, 30 cm, 40 cm and 50 cm in each column. All the samples were placed in 60 mL of sterile water and shaken completely, and then, 10 mL of supernatant was collected to measure the concentration of *E. coli* and to explore the retention of *E. coli* in the medium.

Mathematical simulation

To quantitatively describe the variation of the concentration of *E. coli* during the river infiltration process under conditions of different hydraulic gradients and the concentration of different *E. coli* in the field, mathematical simulation was also carried out in this study. The transport process of *E. coli* in saturated porous media during river infiltration was generalized as a one-dimensional migration problem of continuous concentration constant injection. It was assumed that the initial location of *E. coli* transport ( $x = 0$ ) was the

**Fig. 4** Schematic map of the soil column for transport of bacteria



**Table 1** Column experimental conditions

Number	<i>E. coli</i> concentration (MPN/100 mL)	Temperature (°C)	Velocity (mL/min)
Z1	10,000	4	0.96
Z2	10,000	4	0.72
Z3	10,000	4	0.48
Z4	10,000	8	0.72
Z5	10,000	Glass bottle: 25 Column: 12	0.72

river (Fig. 2). The analytical mathematical model for the transport of *E. coli* during the water infiltration process is as follows:

$$R_d \frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - \lambda R_d C, \quad 0 < x < +\infty, \quad t > 0 \tag{1}$$

The initial and boundary conditions are as follows:

$$\begin{cases} C(x, t)|_{t=0} = 0, & 0 < x < +\infty \\ C(x, t)|_{x=0} = C_0, & t \geq 0 \\ C(x, t)|_{x \rightarrow +\infty} = 0, & t \geq 0 \end{cases} \tag{2}$$

$$R_d = \frac{T_{(50\%E.coli)}}{T_{(50\%Cl^-)}} \tag{3}$$

In formula 1 and 2, *C* is the concentration of *E. coli* (MPN/100 mL) in the water body; *R<sub>d</sub>* is the retention

factor; *D<sub>L</sub>* is the longitudinal hydrodynamic dispersion coefficient (m<sup>2</sup>/d) along the direction of water flow; *u* is the average velocity of the flow (m/d), and *λ* is the first-order filtration coefficient (D<sup>-1</sup>).

The retention factor *R<sub>d</sub>* was calculated as the ratio of non-adsorptive tracers to adsorptive pollutants for half the time required to reach a stable concentration (formula 3). In this study, we also completed the NaCl transport experiment and used the results (data not shown) to obtain a retention factor of 7.5. The dispersion coefficient is an important parameter for the transport of *E. coli*. In this paper, the longitudinal hydrodynamic dispersion coefficient can be calculated by the dispersity and flow velocity, that is, *D<sub>L</sub>* = *α<sub>L</sub>u*, where *α<sub>L</sub>* is directly proportional to the flow distance *x* according to Wang (2008), that is, *α<sub>L</sub>* = 0.1*x*.



## Results

### Characteristics of aquifer sediments

The particle size distribution of the sediment of the riverbed and the aquifer porous medium is shown in Fig. 5. The sediment of the riverbed and aquifer medium at a depth of 4.3 m was loamy sand with a clay content of 0–15% and a silt content of 0–15%. The aquifer medium at a depth of 4.3–8 m was less gravelly soil, and the gravel content (> 2 mm) was 4.24%. In the aquifer medium at a depth of 8–12 m, the gravel content (> 2 mm) was 29.61%, which was gravelly soil.

### Spatial and temporal distribution characteristics of *E. coli*

The curve of the *E. coli* concentration changes along the direction of groundwater flow in August and September 2016 is shown in Fig. 6. The diagram shows that the concentration of *E. coli* decreased rapidly along the direction of flow. Although the content of *E. coli* in the river was different, the *E. coli* removal rates from groundwater samples at distances of 2 m and 4 m from rivers were 96.19% and 99.54% in August and 99.42% and 99.96% in September, respectively.

The concentration of *E. coli* in river water showed a gradual increase from August (435.85 MPN/100 mL) and September (2419.6 MPN/100 mL) to November (much more than 2419.6 MPN/100 mL). There may

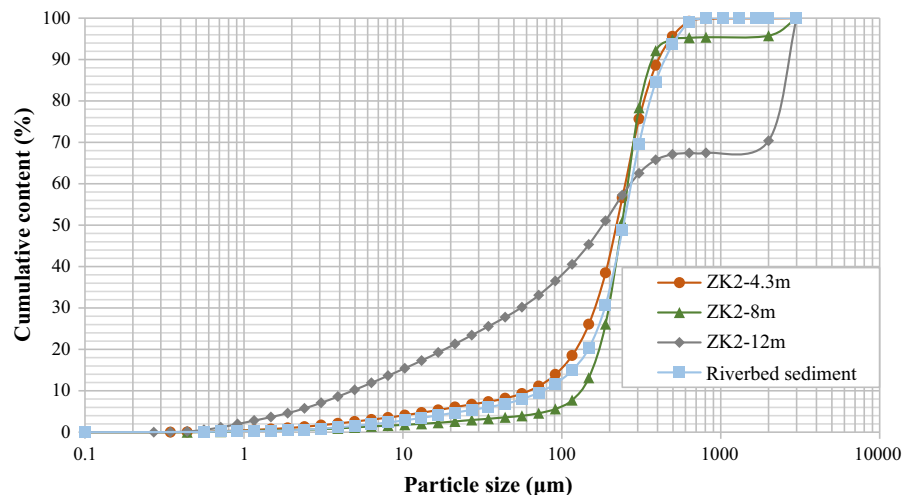
be two reasons for this phenomenon: On the one hand, the temperature in August and September was relatively high. At this time, *E. coli* metabolism was active, so it was easier to metabolize and reduce the concentration. On the other hand, August and September occurred during the wet period, in which the river receives more recharge of atmospheric precipitation, so the dilution effect on *E. coli* is more pronounced.

Despite a high level of *E. coli* in the river in November, there was no detectable level in all the observed groundwater along the river bank. In contrast, although the concentration of *E. coli* was not very high in river water in August and September, the *E. coli* were detected in groundwater. Based on the analysis of the hydro-geological conditions of the site, the water level of the river water rose rapidly in August and September, making the water level difference between the river and the groundwater greater than that in November. Thus, the hydraulic gradient between the river and the groundwater was greater in August and September. This phenomenon increased the speed of the river water infiltration, resulting in a short retention time of water in the medium and an insufficient response to adsorption and filtration. Therefore, *E. coli* was detected in groundwater near the river bank in August and September.

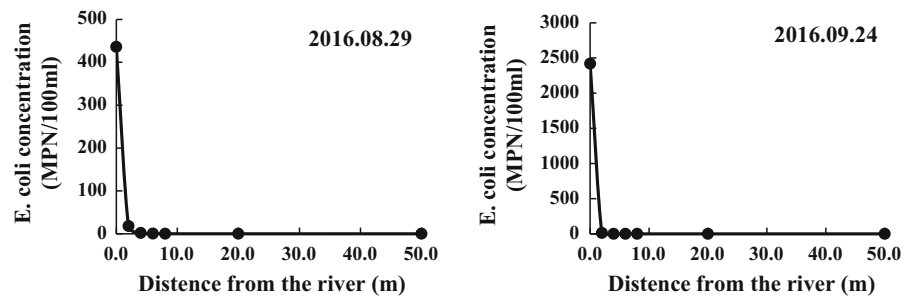
### Influence of hydraulic gradients

In all column experiments, the relative effluent concentrations ( $C/C_0$ , where  $C$  is the effluent and  $C_0$  is the influent concentration) of *E. coli* were plotted as

**Fig. 5** Particle size distribution of sediments and aquifer media



**Fig. 6** *Escherichia coli* concentration curves in the direction of groundwater flow in August and September



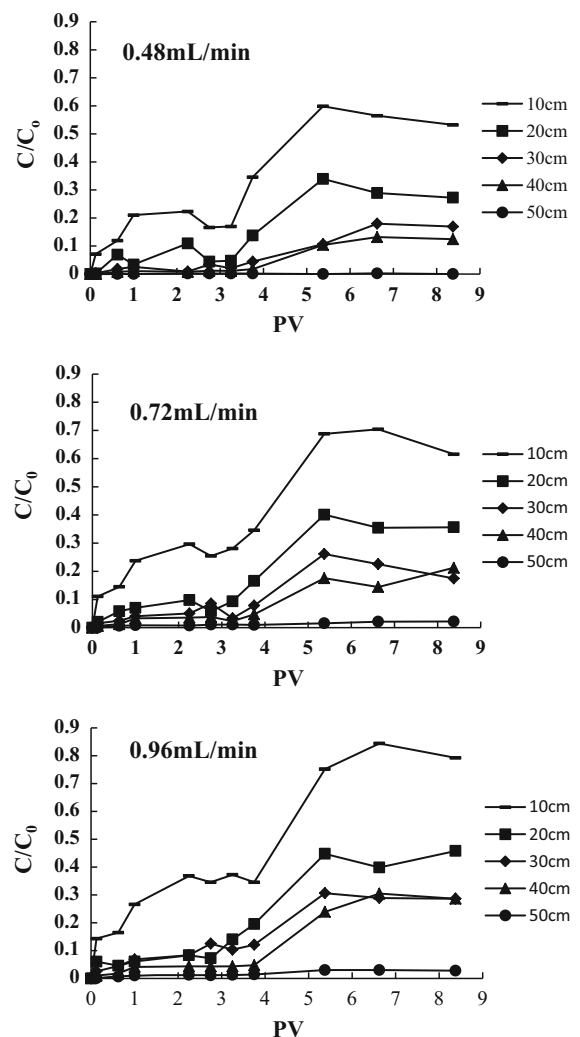
a function of pore volume (PV, total effluent volume/void space volume within the column) for different sampling depths.

Figure 7 shows the breakthrough curves (BTCs) of *E. coli* at different flow rates. This group of experiments were completed at 4 °C, neglecting the growth and metabolism changes of *E. coli*. The curves showed similar characteristics under various flow rates. The BTCs began to plateau at approximately 1 PV and began to increase gradually at approximately 4 PV until remaining relatively stable at approximately 5 PV. The study published by Foppen et al. (2005) proved that the appearance of the plateau was caused by the removal effect of dead-end pores (DEPs). The higher the flow rate was, the greater the concentration of *E. coli* in the effluent was, which was particularly evident in the first 10 cm of the soil column. When the flow rate was increased from 0.48 to 0.96 mL/min, the stable relative concentration ( $C/C_0$ ) at the sample point of 10 cm rapidly increased from 0.6 to 0.9.

#### Influence of temperature

In this part of the experiments, the flow rate was controlled at 0.72 mL/min, and three temperature conditions were designed: 4 °C, 8 °C and 12 °C. The breakthrough curves are shown in Fig. 8.

According to Fig. 8, the breakthrough process of *E. coli* under different temperatures showed different characteristics. Under conditions of 4 °C and 8 °C, the BTCs of *E. coli* at each sampling port had a short period of stagnation (approximately 1 PV) and then gradually increased (4 PV and 2 PV, respectively) and finally reached a relatively stable state (5 PV and 3 PV, respectively). Similarly, the stagnation period at approximately 1 PV was attributed to the removal effect of dead-end pores (DEPs). At 12 °C, the breakthrough curve reached the equilibrium state



**Fig. 7** Breakthrough curve of *E. coli* under different flow rates

directly from 2 PV. It can be concluded that the lower the temperature was, the later the stationary state appeared, that is, there was a lag for the peak value. When the breakthrough curve reached a steady state,



the relative concentration value of *E. coli* ( $C/C_0$ ) in the effluent at each sampling port decreased with the increase in temperature, which indicated that the high temperature condition was more conducive to the removal of *E. coli*.

Numerical simulation results

The migration of *E. coli* during river infiltration in the study area was simulated. The simulation parameters were obtained from empirical or experiential values. Simultaneously, the measured data were used to identify the parameters and validate the model. The model was used to fit the concentration of *E. coli* in August and September 2016. The fitting results are

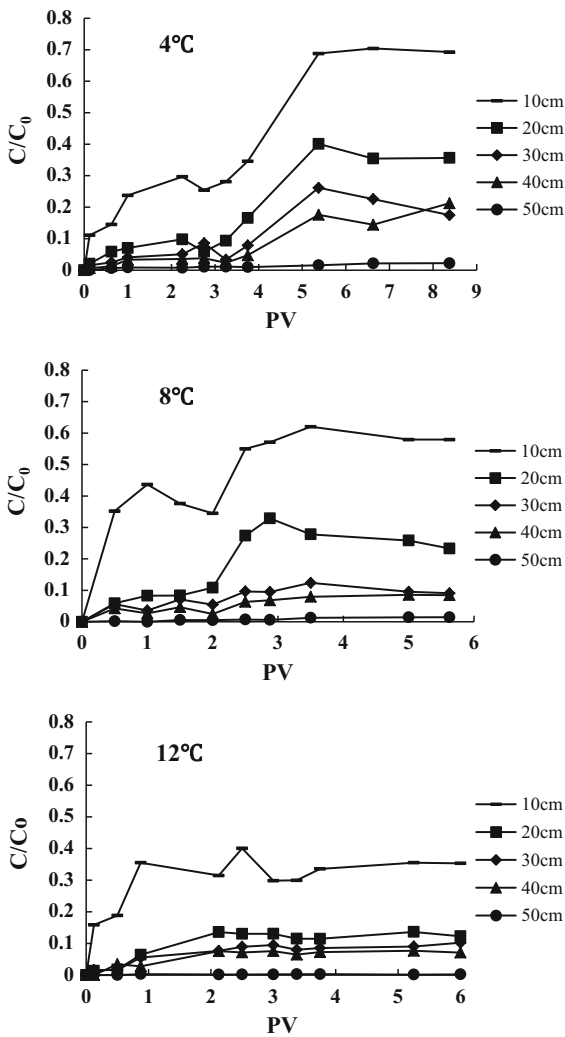


Fig. 8 Breakthrough curves of *E. coli* at different temperatures

shown in Fig. 9. The graph shows that the model fitted the site data better and can be used for forecasting work.

The trends of *E. coli* in the river bank infiltration zone were simulated under conditions of three hydraulic gradients (10%, 15% and 20%), and two cases, a high concentration (2500 MPN/100 mL) and a low concentration (500 MPN/100 mL), of *E. coli* were included in each hydraulic gradient. The simulation results are shown in Table 2.

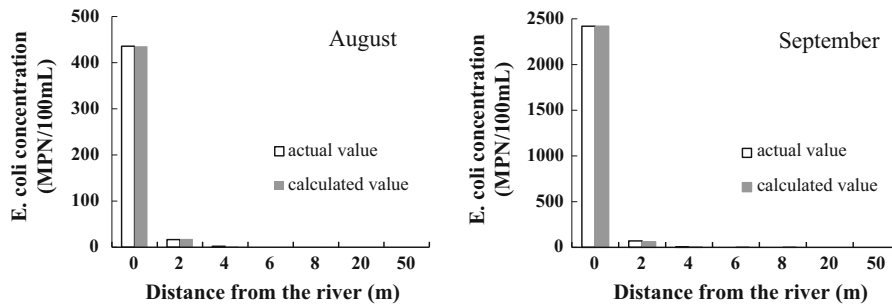
The transport distance in Table 2 refers to the distance from the river bank when the concentration dropped to 1 MPN/100 mL. The hydraulic gradient between the river and the groundwater and the concentration of *E. coli* in the river clearly affected the transport of *E. coli* during river water infiltration. The farthest migration distance of *E. coli* was 4.99 m when the hydraulic gradient was large, but the concentration of *E. coli* in the river was low; it was 3.45 m when the concentration of *E. coli* in the river was high, but the hydraulic gradient was small. Thus, the hydraulic gradient demonstrated the most prominent effect on the migration of *E. coli*.

Table 2 shows that when the hydraulic gradient was largest (20%) and the concentration of *E. coli* in the river was also the largest (2500 MPN/100 mL), the migration distance of *E. coli* could reach approximately 7 m. Therefore, corresponding to the actual condition, when the above situation occurs, it is necessary to reduce the intensity of groundwater exploitation to reduce the hydraulic gradient or to select a well that is far away from the river for mining to reduce the risk of microbial contamination.

Discussion

The removal rate was defined as the ratio of the concentration of *E. coli* remaining in the soil column to the initial concentration after reaching breakthrough equilibrium. The residual concentration in the soil column was calculated by subtracting the concentration of the effluent from the initial concentration.

In the comparative tests of soil columns with different hydraulic gradients, the removal rate increased gradually with the increase in transport distance (Fig. 10), and it demonstrated a good logarithmic relationship with the transport distance. At the same migration position, the removal rate of the three



**Fig. 9** Fitting diagram of the measured concentration and the calculated concentration of the corresponding model

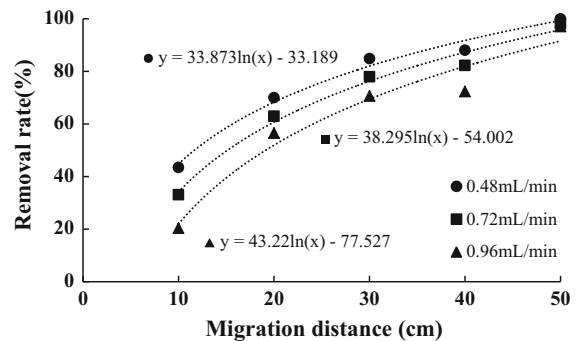
**Table 2** Summary of the *E. coli* migration distance under different hydraulic gradients and *E. coli* concentrations

Hydraulic gradient (%)	Transport distance (m)	
	500 MPN/100 mL	2500 MPN/100 mL
10	2.49	3.45
15	3.74	5.18
20	4.99	6.90

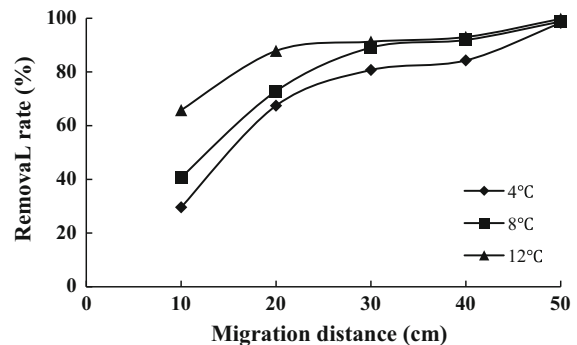
flow rates exhibited increasing order of 0.96, 0.72 and 0.48 mL/min. The removal rates at the column bottom from small to large flow rates were 99.02%, 98.03% and 97.06%, respectively, showing that with increasing distance from the water inlet, *E. coli* could be completely removed. When focusing on transport experiments at different temperatures (Fig. 11), the higher the temperature was, the higher the cumulative removal rate of *E. coli* within the same transport distance was. Thus, the removal rate of the three temperature conditions was 12 °C > 8 °C > 4 °C. With increasing distance from the inlet, the *E. coli* removal rates at the bottom of the column at 4 °C, 8 °C and 12 °C were 98.03%, 98.61% and 99.76%, respectively. In contrast to the curves under different flow rates, the migration distance and removal rate no longer showed a good logarithmic relationship.

The relative retention ratio was the ratio of the retention at a certain depth to the total retention in the soil column. The calculation was performed by dividing the retention of *E. coli* in the medium at a certain depth by the sum of the retention of *E. coli* in the soil column.

According to the relative retention ratio curves under different hydraulic gradients (Fig. 12), the

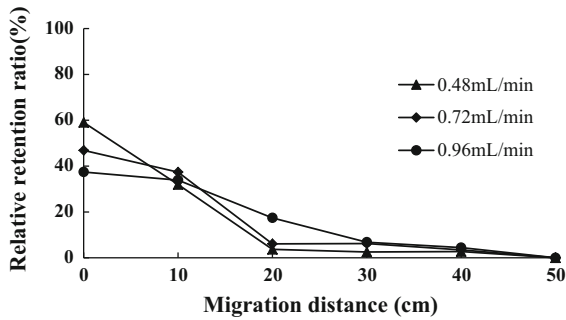


**Fig. 10** Relationship between transport distance and removal rate of *E. coli* under different flow rates

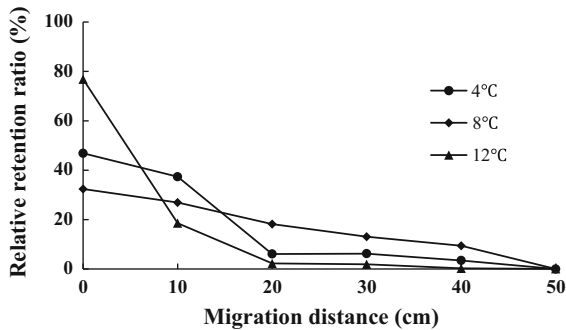


**Fig. 11** Relationship between migration distance and removal rate of *E. coli* under different temperatures

relative retention of the surface layer was largest. The corresponding surface retention ratio was 59.05%, 46.86% and 37.42% from the small to the large flow rates, respectively. As the transport distance increased, the relative retention ratio in the medium generally decreased. From Fig. 12, we can also see that the retention rate curve was the most gradual at 0.96 mL/min, while the 0.48 mL/min curve was the steepest. This is because the higher pore water velocity could



**Fig. 12** Curves of relative retention of *E. coli* in various depth media under different flow rates



**Fig. 13** Curves of relative retention of *E. coli* in various depth media under different temperatures

lead to a shorter residence time of bacteria in the porous medium, which increased the downstream transport of the bacteria to a certain extent and made the removal of bacteria to occur more evenly in the whole transport process, thus reducing the difference in retention in different media.

The relative retention ratio curves of *E. coli* in media at different depths under different temperatures are shown in Fig. 13. The relative retention of *E. coli* in the medium also decreased as the migration distance increased. The relative retention ratio of the surface medium from small to large temperature conditions was 46.86%, 26.93% and 76.84%, respectively, reflecting the good removal effect of the surface medium.

Based on the results of all soil column tests, the retention in loamy sand (0–20 cm) was largest with a relative retention ratio of 20–50%, followed by little gravel soil (20–40 cm) with a relative retention ratio of 5–12%, and the smallest retention ratio of conglomerate soil (40–50 cm). Bradford et al. (2005) noted that the filtration effect should be considered

when the ratio of the length of *E. coli* to the average particle size ( $d_p/d_m$ ) of the medium was greater than 0.17%, and the filtration effect was significant when the ratio is greater than 0.5%. The average particle size of the medium is calculated by the following formula:

$$d_m = (\Phi16 + \Phi50 + \Phi84)/3$$

where  $d_m$  is the average particle size (m) of the medium and  $\Phi16$  is the particle diameter ( $\mu\text{m}$ ) corresponding to the cumulative content of the particle size of 16%, so do  $\Phi50$  and  $\Phi84$ .

The size of *E. coli* in this paper was 0.5  $\mu\text{m}$ , and the particle size distribution of sediments and aquifer media is shown in Fig. 5. The ratio of the size of *E. coli* to loamy sand, a little gravel soil and gravelly soil was 0.23%, 0.22% and 0.06%, respectively. These data indicate that the filtration effect of *E. coli* was strongest in loamy sand and was basically absent in gravelly soil.

In addition, in Fig. 13, the retention of *E. coli* at 4 °C was mainly concentrated in the first 20 cm, while *E. coli* were more evenly delayed in the first 40 cm at 8 °C. Jaynes (1990) and Lentz and Bjorneberg (1999) observed that water infiltration into soil increased with the water temperature, and it was partly attributed to a decrease in the water viscosity, which caused an increase in the hydraulic conductivity. According to this view, an increase in temperature leads to an increase in the velocity of the water, which facilitates the transport of *E. coli*. When the inflow rate of bacteria was approximately the same, the increase in flow velocity caused by the increase in temperature facilitated the transport of *E. coli* over the migration distance. Figure 8 shows that the relative concentration ( $C/C_0$ ) of *E. coli* in the effluent was lower at higher temperatures, reflecting the higher total removal rate of *E. coli* at a high temperature. Therefore, *E. coli* that had not been removed from the first 20 cm at 8 °C was still strongly retained in the deep medium after being conveyed downward, showing a more stable retention characteristic throughout the soil column. This result is consistent with that of Salini Sasidharan et al. (2017), who indicated that an increase in temperature from 4 to 20 °C increased the retention of viruses and latex NPs in porous media under intermediate ionic strength (10 and 30 mM) conditions. In particular, the attachment rate coefficient ( $K_{att}$ ) calculated from fitted model parameters showed an increase of up to 109 under intermediate

ionic strength conditions, and the increase in the retention amount was influenced more by  $K_{\text{nat}}$  than by biological inactivation.

It was interesting that the removal rate of the column surface layer at 12 °C was nearly 77%, and the total removal rate of *E. coli* reached up to 95.41% even in the upper 10 cm. Based on the experimental process, when the *E. coli* solution entered the aqueous medium at 25 °C, the temperature of the medium at which the bacterial liquid was injected into the soil column was higher than 12 °C, and the adsorption capacity of the medium was strong. Concurrently, the growth and reproduction of *E. coli* were accelerated under higher temperature conditions, and the accumulation of growth and metabolism products formed floc material that accumulated on the surface, which inhibited the movement of living bacteria to the deep soil column. As a result, the joint effect of these two factors resulted in a large amount of retention and removal of *E. coli* at the surface.

Through the whole experiments, it can be seen that the difference in water flow velocity due to the change of hydraulic gradient had a significant impact on the migration of *E. coli*, and this effect was most obvious in the initial zone of migration. Therefore, when exploiting groundwater near rivers, the distance between exploiting wells and river banks and the water quality problems that may arise in the case of large exploitation should be considered comprehensively. The increase in groundwater temperature led to a decrease in liquid viscosity and changed the permeability coefficient of the soil, which was conducive to the migration of *E. coli*. However, the increase in temperature would increase the decay rate of microorganisms and the adsorption capacity of the media, as well as increase the removal rate. Therefore, the simple method used in previous experiments to study similar types of bacterial migration at a constant temperature is flawed. The critical temperature of different dominant effects should be further determined in the future to provide more reliable parameters for the removal of *E. coli* and similar bacteria.

## Conclusion

Based on the investigation of the temporal and spatial variation in *E. coli* during the process of river water infiltration in a riverside water source, column

transport experiments were carried out to study the migration of *E. coli* under different hydrodynamic and temperature conditions. Moreover, numerical simulations were performed to assess the variation in *E. coli* concentration characteristics to acquire a quantitative description. The main conclusions of the study are as follows.

1. Under natural conditions, the river bank infiltration zone demonstrated a good removal effect of *E. coli* in this specific area. The concentration of *E. coli* decreased along the flow direction, and the removal rate was greater than 96%.
2. Lower hydraulic gradient and higher temperature conditions enhanced the removal efficiency of *E. coli* in the porous medium. However, according to the variation characteristics of the *E. coli* concentration in the study area, the hydraulic gradient between the river water and groundwater was the most important factor affecting the removal of *E. coli*.
3. The removal rate of *E. coli* from the bottom of the soil column was greater than 97.06% under different hydraulic gradients and temperatures after reaching the penetration equilibrium. Its removal mechanism is mainly adsorption and filtration. Moreover, the effect of surface filtration on the removal of *E. coli* could not be neglected.
4. The results of numerical simulation showed that when the hydraulic gradient was maximal (20%) and the concentration of *E. coli* in the river was largest (2500 MPN/100 mL), the safe mining distance of groundwater that would not cause a risk of *E. coli* pollution was more than 7 m from the river.

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