Effects of Reclaimed Water and C and N on Breakthrough Curves in Sandy Soil and Loam

Fangze Shang, Shumei Ren, Lei Yan, Chong Zhang, Ganlin Wu, Guoya Wang, Chunhuan Zhu

Effects of Reclaimed Water and C and N on Breakthrough Curves in Sandy Soil and Loam

Fangze Shang[1,a], Shumei Ren[1,b], Lei Yan[2,c], Chong Zhang[1,d], Ganlin Wu[1,e], Guoya Wang[1,f], Chunhuan Zhu[1,g],

[1]College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China

[2]State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

[a]shangfangze@126.com, [b]renshumei@126.com, [c]yanl@whu.edu.cn, [d]h54zhangchong@sohu.com, [e]wuganlin530@126.com, [f]18810524293@163.com, [g]shuilizch@cau.edu.cn

Abstract. Long-term irrigation with reclaimed water may change soil physical properties and solute transport rate due to C and N in reclaimed water and the particularity of reclaimed water. Ordinary water, reclaimed water and mixed water which added C and N into reclaimed water were used as background water, then potassium bromide was added to background water and mixed them into three kinds of solutions whose bromide concentrations were all 0.5 mol/L, then soil column breakthrough experiments were conducted. The results showed that bacteria quantity increased both in sandy soil and loam after soil column experiments, and bacteria quantity in sandy soil and loam were all in the following descending order: breakthrough solution using mixed water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using ordinary water as background water. However, fungi quantity had no significant difference. Cumulative infiltration in sandy soil and loam can be properly described by power function and logarithm function, respectively. The amount of cumulative infiltration in sandy soil and loam in the same infiltration time were all showed a descending order as: breakthrough solution using ordinary water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using mixed water as background water. Breakthrough curves can be well described by CXTFIT 2.1 code, it can be seen from the values of *V* and *D* that reclaimed water and the addition of C and N made solute transport more difficult in soils and increased diffusion coefficient, and these impacts were greater on loam than sandy soil. Reclaimed water and the added C and N increased soil bacteria, complicated soil pore system, and decreased soil hydraulic conductivity.

Keywords: reclaimed water, C and N, cumulative infiltration, bacteria, breakthrough curves, CXFIT 2.1

1 Introduction

Reclaimed water irrigation is an effective way to resolve the shortage of conventional water resources in agricultural. In China, agricultural water consumption accounts for more than 60% of the total water consumption [1], and with the development of industrialization and the growth of urban population, conventional water will be more and more used as industrial and domestic water, thus agricultural water will be strictly limited. On the one hand, the quality of secondary reclaimed water is conform to crop irrigation water quality standards [2], on the other hand, Beijing will produce 1.0×10^9 m^3 of reclaimed water per year by 2015, and China will produce more than 680 $\times10^9$ m^3 of reclaimed water in 2030[3], thus it is a good choice that irrigation with reclaimed water in large scale in China. However, reclaimed water can be seen as a coexistence system and many researchers studied the specific effects of reclaimed water irrigation from different aspects. C and N in reclaimed water have important effects on soil microorganisms [4], K^+, Ca^{2+}, Na^+ and Mg^{2+} in reclaimed water may cause soil salinity and the change of soil hydraulic conductivity [5-6], suspended solid particles and colloid in reclaimed water may also clog soil pores.

Soil microorganism is one of the most active parts in soils, and it can influence the biochemical reactions of soils, because C and N are the energy sources of microorganisms activities, thus C/N in soil, soil solution and irrigation water have been studied by many researchers [7]. On the one hand, different urban reclaimed water plants produce different quality of secondary reclaimed water, even the same reclaimed water plant produces different quality of secondary reclaimed water in different seasons, leading to the change of C/N in reclaimed water. On the other hand, agricultural measures such as straw returned to field and fertilization can also change C/N value of soils and soil solutions. Breakthrough curve reflects the hybrid displacement characteristics of solute in different mediums, and it also reflects the balance time between solute and mediums, thus the study of breakthrough curve is an effective way to understand solute transport characteristics in soils [8-9]. CXTFIT code which developed by U.S. Salinity Laboratory and based on Levenberg-Marquardt algorithm, has been widely used to calculate solute transport parameters and describe breakthrough curves [10]. Solute breakthrough curves were obtained from soil column experiment, and the parameters were fitted by using CXTFIT code [11-12].

To our knowledge, most soil column experiments seldom consider the actual change of C/N in soils and soil solutions when agricultural measures like crops straw returned to field, fertilization, and reclaimed water irrigation were taken, and more less to study their effects on solute transport, which is important for agricultural management and environmental protection. Thus, our objectives were: (1) to compare the impact of ordinary water, reclaimed water and mixed water on soil microorganisms and cumulative infiltration; (2) to simulate breakthrough curves by using CXFIT 2.1 code; and (3) to explore the effect of C and N on solute transport.

2 Experiments and Methods

2.1 The Properties of Experiment Soils

Soil samples were collected from Beijing Water Science and Technology Institute experiment station in Tongzhou on April 1, 2013. Sandy soil and loam were collected from 120-160 cm and 0-20 cm soil layers, respectively. The percentage of sand, silt, and clay in sandy soil is 88.4%, 10.1% and 1.5%, respectively, and the percentage of sand, silt, and clay in loam is 40.8%, 48.9% and 10.3%, respectively. Physical and chemical properties of soils were shown in Table 1.

Table 1. Physical and chemical properties of experiment soils

Soil texture	pH value	Bulk density	$EC_{1:5}$	TN^a	TP^b	TK^c	Organic C
		($g\cdot cm^{-3}$)	($\mu s\cdot cm^{-1}$)	($mg\cdot kg^{-1}$)	($mg\cdot kg^{-1}$)	($mg\cdot kg^{-1}$)	%
Sandy soil	8.9	1.50	120.0	400.5	2.5	15.4	0.17
Loam	8.5	1.45	210.0	1103.4	23.1	98.7	0.45

[a]TN=total nitrogen, [b]TP=total phosphorus, [c]TK=total potassium

2.2 Experimental Design

The reclaimed water was secondary precipitation water taken from Qinghe sewage treatment plant of Beijing, ordinary water was tap water taken from China Agricultural University. Ammonium chloride was added to reclaimed water so that the concentration of total nitrogen up to 80 mg/L, then glucose was added so that the C/N=7 in mixed water. Ordinary water, reclaimed water and mixed water were used as background water, and their chemical characteristics were presented in Table 2. Then potassium bromide was added to background waters, respectively, and finally mixed into three kinds of solutions whose bromide concentration were all 0.5 mol/L. A-1, A-2 and A-3 denoted breakthrough solution using ordinary water, reclaimed water and mixed water as background water to infiltration sandy soil, respectively. B-1, B-2 and B-3 denoted breakthrough solution using ordinary water, reclaimed water and mixed water as background water to infiltration loam, respectively.

Table 2. Important chemical characteristics of the three kinds of background water

Parameters	Background water types		
	Ordinary water	Reclaimed water	Mixed water
pH	7.8	7.6	7.6
EC ($dS\cdot m^{-1}$)	0.72	1.37	1.42
Total nitrogen ($mg\cdot L^{-1}$)	2.0	30.1	90.0
NO_3^--N ($mg\cdot L^{-1}$)	0.1	15.7	15.7
NH_4^+-N ($mg\cdot L^{-1}$)	0.1	0.3	60.3
Organic carbon ($mg\cdot L^{-1}$)	0.5	50.8	630.0
DOM ($mg\cdot L^{-1}$)	3.8	25.0	672.0
TSS^a ($mg\cdot L^{-1}$)	1.5	6.7	6.7
K^+ ($mg\cdot L^{-1}$)	7.5	8.8	8.8
Ca^{2+} ($mg\cdot L^{-1}$)	48.2	90.3	90.3
Na^+ ($mg\cdot L^{-1}$)	12.3	100.5	100.5
Mg^{2+} ($mg\cdot L^{-1}$)	15.7	38.9	38.9

[a]TSS = total suspended solids

2.3 Soil Column

Soil column and markov bottle were made of organic glass, the inner diameter and height of soil column was 9 cm and 40 cm, respectively, and there was a water inlet and outlet at the top and bottom of soil column, respectively. The inner diameter and height of markov bottle was 9 cm and 50 cm, respectively. Quartz sands whose particle size between 0.2 and 0.4 cm and between 0.8 and 1.5 cm were used as filter layer, and the height was 3 cm, and a piece of filter paper was put on the filter layer, then sandy soil column was packed according to bulk density of sandy soil (1.5 g/cm^3), and the total thickness was 30 cm, loam soil column was packed according to the bulk density of loam (1.45 g/cm^3), and the total thickness was 30 cm, then a little of quartz sand whose particle size between 0.2 and 0.4 cm was added. Infiltration water head was 5 cm for all soil columns (two replications).

2.4 Samples Testing and Data Analysis Methods

Experiments were started on May 1, 2013, continued sampling with 100 ml plastic bottles, and recorded the sampling time of each sample， and the water samples were filtered with 0.45 μm membrane filtration, then stored in 4 ^{0}C fridge. The PIC-10 ion chromatograph was used to measure the concentration of bromide. Fluorescence quantitative polymerase chain reaction (PCR) method was used to measure soil bacteria and fungi quantity. Dates were analyzed using SPSS 17.0 software, and significance level was selected at 0.05.

The convective-dispersive equation can be expressed to [13]:

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial X^2} - V\frac{\partial C}{\partial X} - - - - - (1)$$

Where X was distance, cm; t was time, h; R was retardation factor, bromide was a non reactive factor, thus R=1; C was the concentration of bromide, mol/L; D was dispersion coefficient, cm^2/d; V was the average pore water flow velocity, cm/d.

3 Results and Discussion

3.1 Effects of Different Breakthrough Solutions on Soil Microorganisms Quantity

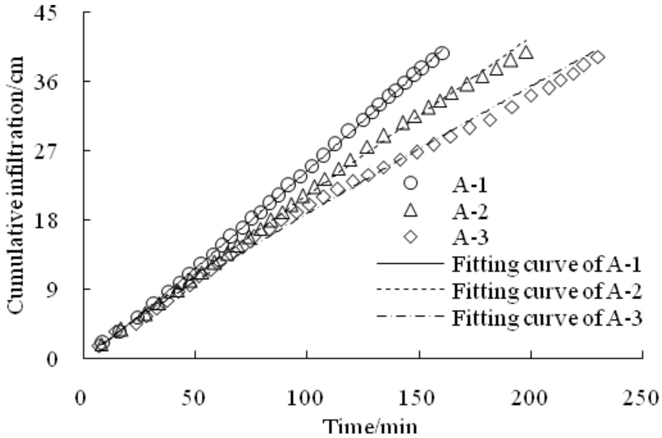
Soil microorganisms including bacteria, fungi, actinomycetes and algae, and the bacteria and fungi account for the largest proportion among them, and C and N are the energy sources for the growth and activity of soil microorganisms. Table 3 showed average soil bacteria and fungi quantity in soil layers after breakthrough experiments. Soil bacteria quantity in sandy soil and loam were all in the following descending order: breakthrough solution using mixed water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using ordinary water as background water. However, soil fungi quantity both in sandy soil and loam had no significant difference in different treatments. It is worth mentioning that bacteria and fungi quantity in loam was about 5 and 80 times that of sandy soil, respectively, and bacteria quantity in sandy soil and loam was about 230 and 13 times that of fungi, respectively. Some researchers found that soil microorganisms quantity increased after added fructose and amino acids, and soil structure could also affect soil microorganisms [14-15]. Reclaimed water had higher concentrations of total nitrogen and organic carbon than ordinary water, thus it provided more energy for the growth of microorganisms, and the addition of C and N sources also promoted the activity of soil microorganisms, especially for bacteria. Because solution infiltration in sandy soil was faster than in loam, microorganisms in sandy soil couldn't use C and N effectively, thus microorganisms quantity in sandy soil were less than in loam.

Table 3. Soil bacteria and fungi quantity in sandy soil and loam

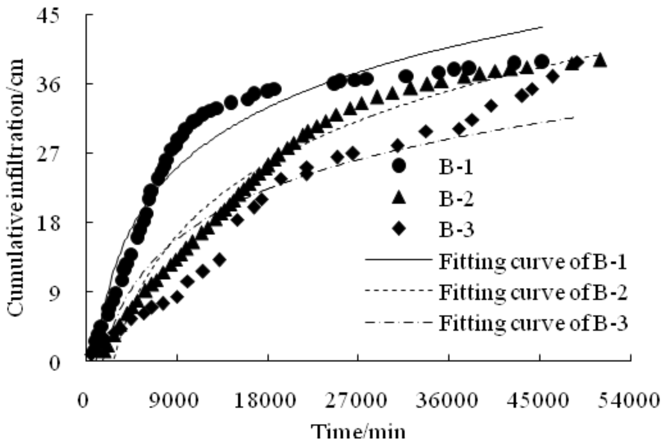
Soil microorganisms types	In sandy soil			In loam		
	A-1	A-2	A-3	B-1	B-2	B-3
Bacteria/(10^6 /g soil)	0.04^a	0.13^b	0.75^c	0.98^a	1.32^b	1.74^c
Fungi/(10^5/g soil)	0.01^a	0.02^a	0.01^a	1.04^a	1.11^a	0.99^a

3.2 Effects of Different Breakthrough Solutions on Cumulative Infiltration

The relationship between cumulative infiltration and infiltration time was shown in Figure 1. Three cumulative infiltration curves had similar shape in sandy soil, and the amount of cumulative infiltration in the same infiltration time showed a descending order as A-1, A-2 and A-3. Three cumulative infiltration curves also had similar shape in loam, and the amount of cumulative infiltration in the same infiltration time decreased in the order of B-1, B-2 and B-3. Compared with breakthrough solution using ordinary water as background water, infiltration rate was reduced after infiltration with breakthrough solution using reclaimed water as background water, and infiltration rate was the lowest after infiltration with breakthrough solution using mixed water as background water. Infiltration rate in sandy soil was quicker than in loam when infiltration with the same solution, also the infiltration rate was stable in sandy soil, while the infiltration rate gradually reduced with the increase of infiltration time in loam. Kostiakov put forward that cumulative infiltration could be expressed in power function [16], while in our study, cumulative infiltration could be expressed with power function and logarithm function in sandy soil and loam, respectively (Table 4). The fitting accuracy was higher in sandy soil than in loam, which meant that solution infiltration in loam was more complex than in sandy soil, and reclaimed water and C and N had significant effect on soil hydraulic conductivity.



(a)Sandy soil



(b) Loam

Figure. 1. Soil cumulative infiltration in sandy soil and loam

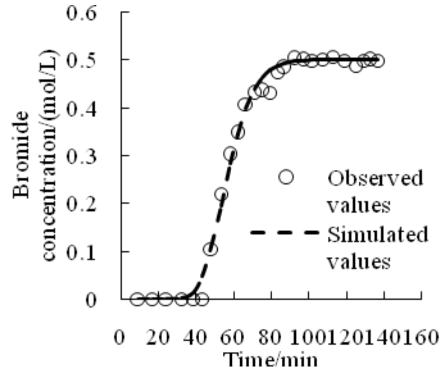
Table 4. Fitting equation of cumulative infiltration in sandy soil and loam

Treatments	Fitting equation	R^2	Treatments	Fitting equation	R^2
A-1	$I=0.188t^{1.055}$	0.999	B-1	I=11.31ln(t)-77.85	0.939
A-2	$I=0.234t^{0.977}$	0.999	B-2	I=13.60ln(t)-107.6	0.963
A-3	$I=0.286t^{0.908}$	0.996	B-3	I=9.348ln(t)-69.24	0.857

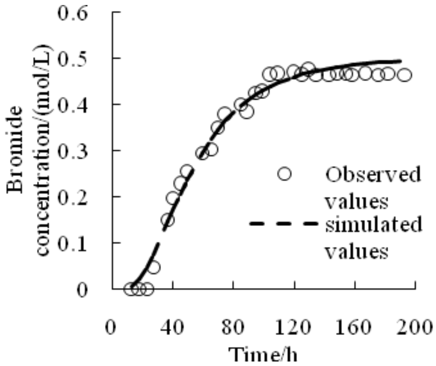
3.3 Effects of Different Breakthrough Solutions on Bromide Breakthrough Curves and Parameters

The breakthrough curves of bromide in different treatments were shown in Figure 2. Soil bulk density and texture determined breakthrough time and breakthrough curve's shape. Soil bulk density affect breakthrough curve [17], compared with loam, sandy soil had less clay content, larger bulk density and more soil macropores, thus bromide breakthrough time was less than 160 minutes in sandy soil but more than 220 hours in loam, also breakthrough curves were steep in sandy soil but gentle in loam. Bromide breakthrough time was the longest in sandy soil infiltration with breakthrough solution using reclaimed water as background water, and there was no difference between other two solutions. Bromide breakthrough time in loam was in the following descending order: breakthrough solution using mixed water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using ordinary water as background water, which showed that bromide transport in loam was more complex with reclaimed water, because suspended solid particles in reclaimed water and the dispersion effect of DOM may block the soil pores[18-19], and it became the most complex scenario when C and N were added.

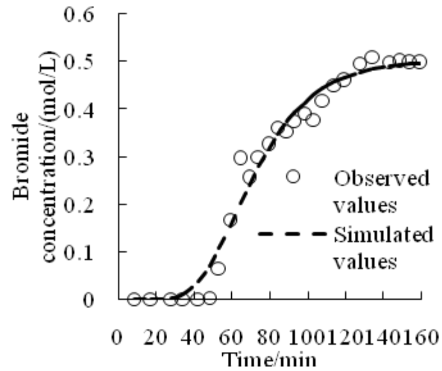
CXTFIT 2.1 code was used to simulate breakthrough curves, $R^2 > 0.97$ (Table 5), which meant simulation accuracy was high, and the calculated parameters were reliable. Soil pore water flow velocity in sandy soil was larger than in loam. In sandy soil, dispersion coefficient was the largest when breakthrough solution using reclaimed water as background water, while in loam, dispersion coefficient was the largest when breakthrough solution using mixed water as background water, which showed that reclaimed water and C and N made the soil pores more complex and increased dispersion coefficient.



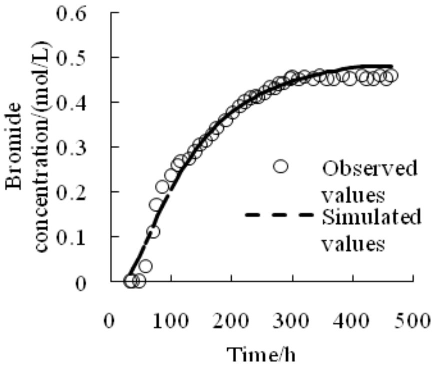
(a) A-1



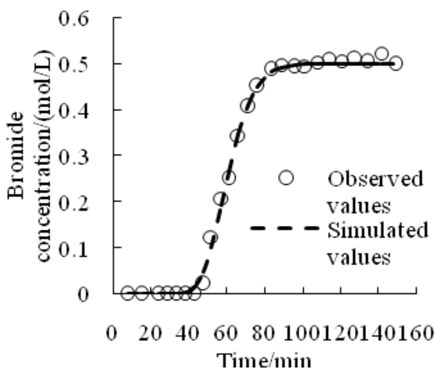
(d) B-1



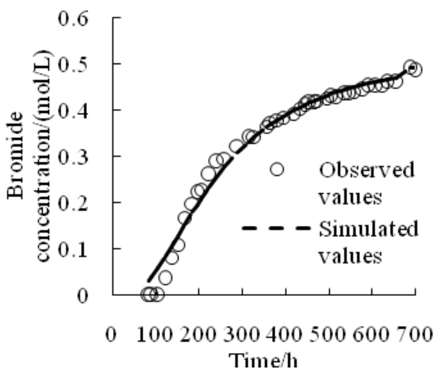
(b) A-2



(e) B-2



(c) A-3



(f) B-3

Figure. 2. Bromide breakthrough curves and simulated values in sandy soil and loam

Table 5. Simulation parameters of bromide transport in sandy soil and loam

Treatments	*V*	*D*	R^2	Treatments	*V*	*D*	R^2
	cm/h	cm^2/h			cm/h	cm^2/h	
A-1	32.10	0.33	0.997	B-1	0.61	4.13	0.985
A-2	25.68	0.86	0.975	B-2	0.27	3.20	0.982
A-3	29.94	0.26	0.998	B-3	0.13	1.19	0.982

4 Conclusions

According to soil column experiments, ordinary water, reclaimed water and mixed water were used as background water, then potassium bromide was added to background water and mixed them into three kinds of solutions whose bromide concentrations were all 0.5 mol/L. After that, soil column breakthrough experiments were conducted in sandy soil and loam. The results showed that bacteria quantity increased both in sandy soil and loam after soil column experiments, and soil bacteria quantity were all in the following descending order: breakthrough solution using mixed water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using ordinary water as background water. However, fungi quantity had no significant difference, and bacteria and fungi quantity in loam were larger than in sandy soil, and bacteria quantity were also larger than fungi both in sandy soil and loam. Infiltration rate in sandy soil was greater than in loam, cumulative infiltration in sandy soil and loam can be properly described by power function and logarithm function, respectively. The amount of cumulative infiltration in sandy soil and loam in the same infiltration time were all showed a descending order as: breakthrough solution using ordinary water as background water, breakthrough solution using reclaimed water as background water, and breakthrough solution using mixed water as background water, which indicated reclaimed water and the added C and N increased soil bacteria, decreased soil hydraulic conductivity, and complicated soil pores system. Breakthrough curves can be well described by CXTFIT 2.1 code, and it can be seen from the values of *V* and *D* that reclaimed water and the addition of C and N made solute transport more difficultly in soils and increased diffusion coefficient, moreover, these impacts were greater on loam than sandy soil. It is necessary to pay attention to the concentrations of C and N in reclaimed water if reclaimed water was used as long-term irrigation water.

Acknowledgment

Fund for this research was provided by the National Natural Science Foundation of China (No.51279204).

References

1. Hu S. Y. China water resources bulletin[M]. Beijing, China WaterPower Press, 2013, 30-31.
2. Chen W. P., Lu S. D., Jiao W. T., et al. Reclaimed water: A safe irrigation water source?[J]. Environmental Development, 2013, 8:74–83.
3. Xue Y. D., Yang P. L., Luo Y. P., et al. Characteristics and driven factors of nitrous oxide and carbon dioxide emissions in soil irrigated with treated wastewater[J]. Journal of Integrative Agriculture, 2012, 11(8): 1354-1364.
4. Acea M. J., Prieto-Ferna´ndez A., Diz-Cid N. Cyanobacterial inoculation of heated soils: effect on microorganisms of C and N cycles and on chemical composition in soil surface[J]. Soil Biology & Biochemistry, 2003, 35(4):513–524.
5. Muyen Z., Moore G. A., Wrigley R. J. Soil salinity and sodicity effects of wastewater irrigation in South East Australia[J]. Agricultural Water Management, 2011, 99(1): 33-41.
6. Shang F. Z., Ren S. M., Zou T., et al. Impact of simulated irrigation with treated wastewater and saline-sodic solutions on soil hydraulic conductivity, pores distribution and fractal dimension[J]. Computer and Computing Technologies in Agriculture VII, IFIP Advances in Information and Communication Technology, 2014, 419:502-516.
7. Wichern F., Mayer J., Joergensen R. G., et al. Release of C and N from roots of peas and oats and their availability to soil microorganisms [J]. Soil Biology & Biochemistry, 2007, 39(11): 2829-2839.
8. Lee M. J., Hwang S. I., Ro H. M. Interpreting the effect of soil texture on transport and removal of nitrate-N in saline coastal tidal flats under steady-state flow condition[J]. Continental Shelf Research, 2014, 84:35–42.
9. Marín-Benito J. M., Brown C. D., Herrero-Hernández E., et al. Use of raw or incubated organic wastes as amendments in reducing pesticide leaching through soil columns[J]. Science of the Total Environment, 2013, 463-464:589-599.
10. Toride N., Leij F. J., van Genuchten M. Th. The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments[M]. Version 2.0, Research Report No. 137. U. S. Salinity Laboratory, Riverside. California. 1995.
11. Martínez-Lladó X., Valderrama C., Rovira M., et al. Sorption and mobility of Sb (V) in calcareous soils of Catalonia (NE Spain): Batch and column experiments[J]. Geoderma, 2011, 160(3/4):468-476.
12. Roger B., Herbert J. Implications of non-equilibrium transport in heterogeneous reactive barrier systems: Evidence from laboratory denitrification experiments[J]. Journal of Contaminant Hydrology, 2011, 123(1/2):30-39.
13. van Genuchten M T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils[J]. Soil Sciece Society of America Journal, 1980, 44:892-898.

14. Wild B., Schnecker J., Eloy Alves R. J., et al. Input of easily available organic C and N stimulates microbial decomposition of soil organic matter in arctic permafrost soil[J]. Soil Biology & Biochemistry, 2014, 75:143-151.
15. Jin V. L., Haney R. L., Fay P. A., et al. Soil type and moisture regime control microbial C and N mineralization in grassland soils more than atmospheric CO_2-induced changes in litter quality[J]. Soil Biology & Biochemistry, 2013, 58:172-180.
16. Kostyakov A. N. On the dynamics of the coefficient of water-percolation in soils and on the necessity for studying it from a dynamic point of view for purpose of amelioration(en ruso): Gramingen, Holanda[J].Transactions, 1932:17-21.
17. Safadoust A., Mahboubi A. A., Mosaddeghi M. R., et al. Effect of regenerated soil structure on unsaturated transport of Escherichia coli and bromide[J]. Journal of Hydrology, 430-431: 80-90.
18. Shang F. Z., Ren S. M., Zou T., et al. Effects of infiltration and evaporation with treated wastewater and salt solutions on soil moisture and salinize-alkalization[J]. Transactions of the CSAE, 2013, 29(14): 120-129.
19. Lado M., Ben-Hur M. Effects of irrigation with different effluents on saturated hydraulic conductivity of arid and semiarid soils[J]. Soil Science Society of America Journal, 2010, 74(1): 23-32.