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RESEARCH ARTICLE

Analysis for remedial alternatives of unregulated municipal solid waste landfills leachate-contaminated groundwater

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Abstract A groundwater flow and solute transport model was developed using Visual Modflow for forecasting contaminant transport and assessing effects of remedial alternatives based on a case study of an unregulated landfill leachate-contaminated groundwater in eastern China. The results showed that arsenic plume was to reach the pumping well in the downstream farmland after eight years, and the longest lateral and longitudinal distance of arsenic plume was to reach 200 m and 260 m, respectively. But the area of high concentration region of arsenic plume was not to obviously increase from eight years to ten years and the plume was to spread to the downstream river and the farmland region after 20 years; while the landfill's ground was hardened, the plume was not to reach the downstream farmland region after eight years; when the pumping well was installed in the plume downstream and discharge rate was 200 m^3/d, the plume was to be effectively restrained; for leakage-proof barriers, it might effectively protect the groundwater of sensitive objects within an extent time range. But for the continuous point source, the plume was still to circle the leakage-proof barrier; when discharge rate of drainage ditches was 170.26 m^3/d, the plume was effectively controlled; the comprehensive method combining ground-harden with drainage ditches could get the best effect in controlling contaminant diffusion, and the discharge rate was to be reduced to 111.43 m^3/d. Therefore, the comprehensive remedial alternative combining ground-harden with drainage ditch will be recommended for preventing groundwater contamination when leachate leakage has happened in unregulated landfills.

Keywords unregulated landfill, groundwater, numerical simulation, contaminant transport, arsenic, remedial alternative

1 Introduction

There are thousands of unregulated municipal solid waste landfills in China that pose significant risk of groundwater to human health (Zhang and Fang, 2006; Han et al., 2011). Unregulated municipal solid waste landfills have hardly any leakage-proof countermeasure, which resulted in the entry of leachate into aquifers (Kjeldsen, 1993; Wang and Zhao, 2002; Guo et al., 2009). Therefore, it is important for groundwater contamination risk management of unregulated municipal solid waste landfills that contaminants transport and fate in groundwater and effects of groundwater remedial alternatives are clearly known (Zhang et al., 2010a; Ma et al., 2012).

Generally, selection of a suitable groundwater remedial alternative for a landfill should firstly be based on the characterization of solid waste and the surrounding natural environment, and then the alternatives should be screened by indoor or field experiments (Guo et al., 2009). However, this procedure often takes a long period and high cost. With the development of numerical model and application of computer simulation technique in groundwater contamination (Zheng et al., 1991; Foose et al., 2001; Wang and McTernan, 2002; Li et al., 2004; Tsanis, 2006; Zheng and Bennett, 2009; Shi et al., 2010), the effects of groundwater remedial alternatives in landfills can

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be achieved by numerical simulation. It can greatly reduce the time and cost.

Presently, Visual Modflow has been widely applied in simulation of contaminants transport and fate. Gurunadha et al. (2001) developed groundwater flow and mass transport models using Visual Modflow software for assessing the extent of migration of contaminants of chemical and pharmaceutical industries in groundwater. Zhang et al. (2007) built up two-dimensional unconfined flow and nitrate transport models for a long period of 42 years by using Visual Modflow for forecasting the concentration change of nitrate. Rajamanickam and Nagan (2010) established a model using Visual Modflow for simulation of the groundwater quality change for next 15 years under five difference scenarios of Textile dyeing effluent discharge. Ma et al. (2012) developed groundwater flow and Cr^{6+} transport models by applying Visual Modflow software for simulating Cr^{6+} transport in groundwater and assessing the effects of controlling contamination. However, the previous studies that have been reported about contaminants transport in aquifers by numerical simulation are seldom focused on arsenic ion and few studies are focused on unregulated landfills. Furthermore, groundwater contamination control is still in the early stage in China and many efforts are urgently needed to improve groundwater contamination control techniques.

In this research, an unregulated municipal solid waste landfill in eastern China was selected to assess the efficiency of several groundwater remedial alternatives. Arsenic was detected to be the main target contaminant in the study site. A groundwater flow and solute transport model was established for simulating the transport and fate of arsenic in groundwater, and the effects of five kinds of groundwater remedial alternatives were assessed based on the simulation results. The alternatives included hardening ground, pumping wells, leakage-proof barriers, drainage ditches and a comprehensive method. The assessment results will assist in drafting a control plan for unregulated landfill leachate-contaminated groundwater.

2 Materials and method

2.1 Site description

2.1.1 Scope of the study site

The unregulated municipal solid waste landfill is situated in the east of Zhejiang Province, China. The study area is approximately 30 hectares and the study scope contains the unregulated municipal solid waste landfill and its surrounding reservoirs, rivers and farmland, where there are coastal lands in the north, a mutual lake in the west, and rivers and farmland in the east and the south, as shown in Fig. 1. The landfill has been operated for about ten years for accepting solid waste from the urban area as well as its surrounding villages.

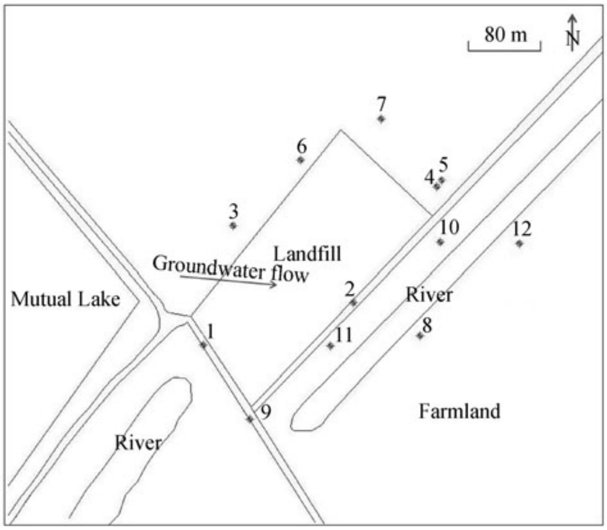


Fig. 1 Layout sketch of the study site.

2.1.2 Hydrogeologic characteristics

The study site is located in the cross region between the low-land terrain of eastern Zhejiang and the plain terrain of northern Zhejiang. It belongs to Yaojiang plain, whose topography is flat and open. The terrain feature is relatively simple, completely covered by the quaternary system deposit. The geological structure belongs to the quaternary alluvium. The strata were divided into six engineering geological layers and eleven sub-layers from above to below, as shown in Table 1. Meanwhile, groundwater was primarily in the form of fracture water and reserved in the forth and the sixth strata.

According to the actual investigation and measurement, the depth to water table is 1.55–2.10 m; rainfall is a primary recharge path; the average annual rainfall is 1100–1900 mm; the average annual rainfall period is 152 d (mainly is in March and September). Furthermore, the groundwater is recharged by an upstream mutual lake and discharges to its downstream river.

2.1.3 Groundwater contamination

By collecting and analyzing groundwater and soil samples in the study site, contrasting the main contaminants of the leachate, and referring to the 3rd level standard of quality standard for groundwater (GB/T14848–1993), the results indicated that contaminants had leached and contaminated the water-table aquifer. The main contaminants contained inorganic contaminants (e.g., ammonia nitrogen, total hardness, and arsenic), organic contaminations (e.g.,

Table 1 Primary geological layers distribution of the study site

Soil series	Strata name	Depth/m	Thickness/m
1	Silt	0.50–1.90	0.50–1.90
2	Mucky silty clay and silt cross layer	1.40–6.30	0.50–5.40
3–1	Silt	3.10–5.70	1.20–3.40
3–2	Silt	5.20–7.00	1.40–4.10
3–3	Silt	15.90–16.70	10.90–12.10
3–4	Silt and mucky silty clay cross layer	14.80–16.20	7.80–13.10
3–5	Silt	14.80–18.60	2.50–5.40
4	Mucky silty clay	40.80–40.80	2.50–5.40
5–1	Silt mixed silty sand	43.00–43.00	2.20–2.20
5–2	Silty sand	51.80–51.80	8.80–8.80
6	Silty clay	–	–

aniline, 4-chloroaniline and Phenol), coli bacillus, and total bacterial count. Meanwhile, it was found that arsenic was the most important contaminant which has exceeded the standard by about thirty times.

2.2 Conceptual model development

2.2.1 Hydrogeological conceptual model

2.2.1.1 Generalization of the aquifer structure

In the vertical direction, the established model was conceptualized as three layers, representing respectively: the water-table aquifer, the average thickness was about 22 m, mainly composed of silt; the upper aquitard, the average thickness was about 14 m, mainly composed of clay; and the confined aquifer, the average thickness was about 66 m, mainly composed of silty sand. In the simulation process of contaminants transport, each aquifer was assumed to be homogeneous and isotropic. The hydraulic gradient was brought from water head between the mutual lake and the surrounding water-table aquifer. Meanwhile, the aquifers were closely related to the surrounding surface waters, which were mainly decided by vertical permeability coefficient. Permeability coefficients were higher than 1.0×10^{-7}cm/s.

2.2.1.2 Generalization of the aquifer boundary

The groundwater of the site had not been largely extracted so far, and there was no obviously natural naked water head. Farmland was a primary land type in the south of the landfill, and its irrigation partly depended on the groundwater. However, considering that the farmland mainly belonged to dry farming, the recharge rate for groundwater was relatively low. Therefore, for simplifying the simulation, the recharge from the rainfall and the mutual lake were mainly considered. Meanwhile, since the study scope was relatively smaller, which couldn't reach natural boundary and a constant flow boundary was determined; the surrounding surface rivers, located in the west and the south of landfill, their boundaries were conceptualized as river boundaries; due to the mutual lake's water level was higher than the groundwater level, then there was a recharge relationship from the mutual lake to groundwater of the site, so the eastern boundary was conceptualized as a constant water-head boundary; the uppermost boundary was conceptualized as water table, which was mainly recharged by rainfall; the lowermost boundary in the bottom of fracture aquifer was conceptualized as non-flow boundary. The lateral flow rate of boundary could be acquired by applying Darcy Law (Lu, 2003; Shen and Jiang, 2008; Ezekwe et al., 2012).

2.2.2 Flow and solute transport model

A groundwater flow and solute transport model was established using Visual Modflow 4.1. Finite difference discretization method was adopted to divide a simulation area of 100 m^2, with 60 × 50 grids generated. Meanwhile, in order to simplify the impacts of flow change to contaminants transport, the groundwater flow was assumed to be steady-state.

The scope and boundary of the solute transport model were in accordance with that of the groundwater flow model. The boundary's characteristics were handled by a known arsenic concentration range. In the simulation process, the impacts of temperature and water density on the hydrodynamic and concentration fields were neglected. The model parameters were completely defined as conservative type. Moreover, the simulation process was based on the assumption that the pollutant source was seen as continuous point source and the source scope was the whole landfill. According to the multi-station monitoring data of the leachate in the landfill, the source intensity was determined as 1.5 mg/L. The arsenic transport was simulated using the MT3DMS module of Visual Modflow.

The observed data from January 1st 2010 and December 31st 2010 (365 d) were input to the simulation model for identifying the hydrogeological parameters; the observed data from January 1st, 2011 to May 31st, 2011(151 d) were used for verifying modeling parameters, boundary characteristics, and the recharge and discharge rate.

2.3 Model calibration and verification

Model calibration was carried out for the existing steady-state condition, since adequate data for transient calibration were not available. During the calibration process, variations in the various hydraulic parameters and model configurations were introduced. The calibration results were assessed by the fitting curve between calculated and observed water level data, as well as arsenic concentration.

In the calibration process, firstly inputting parameters of groundwater flow model, to establish flow model, then inputting parameters of solute transport model, and operating calibration. The manual calibration was used in the simulation process. WHS method, that was a kind of faster convergence and stable solution, was applied to solve flow model, and the observed data were used to calibrate the model. All source and sink items were regarded as recharge or discharge intensity, rainfall infiltration and lateral run-off of the mutual lake was main recharge source, and the downstream river was the primary discharge way. GCG, an implicit method, was applied to solve convection item of the solute transport model, and that was operated by MT3DMS module (Hussein and Schwartz, 2003; Liu and Chen, 2006; Zheng et al., 2011).

It was obtained from the calibration process that the ratio of each layer's transverse dispersity to longitudinal dispersity was 0.1 and the ratio of vertical dispersity to longitudinal dispersity was 0.01. Other related parameters input to the model were shown in Table 2. These parameters were found agreeable because the calculated values of water level and arsenic concentration were essentially consistent with the observed values, as shown in Figs. 2(a) and 2(b).

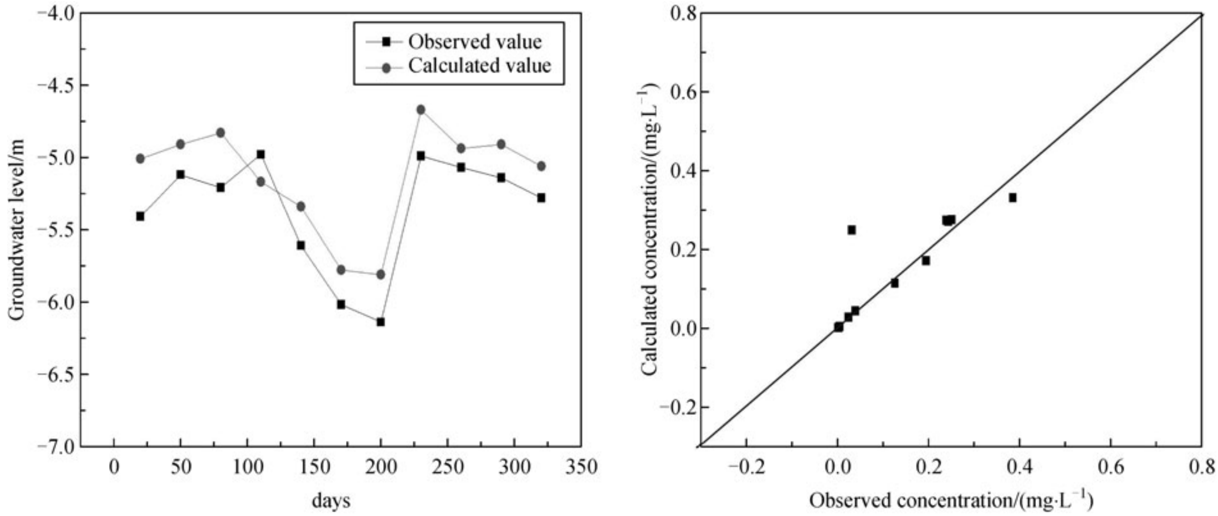
3 Results and discussion

3.1 Contaminant transport forecast

Under the condition of no pollutant source controlling countermeasures, the established groundwater flow and solute transport coupled model was applied to simulate arsenic transport in the water-table aquifer, and the simulation periods were five years (1825 d), eight years (2920 d), ten years (3650 d), and twenty years (7300 d), respectively. Since the pollutant source was supposed as continuously injected point source, arsenic plume was to

Table 2 Parameters of the groundwater flow model

Aquifer style	Water supply degree	Water storage rate	K_x,K_y/(m·d^{-1})	K_z/(m·d^{-1})	Rainfall recharge coefficient
Water-table aquifer	0.2	1×10^{-5}	3.03×10^{-5}	3.03×10^{-5}	0.25
The upper aquitard	0.2	1×10^{-5}	1×10^{-8}	1×10^{-8}	–
Confined aquifer	0.2	1×10^{-5}	1×10^{-6}	1×10^{-6}	–



(a) (b)

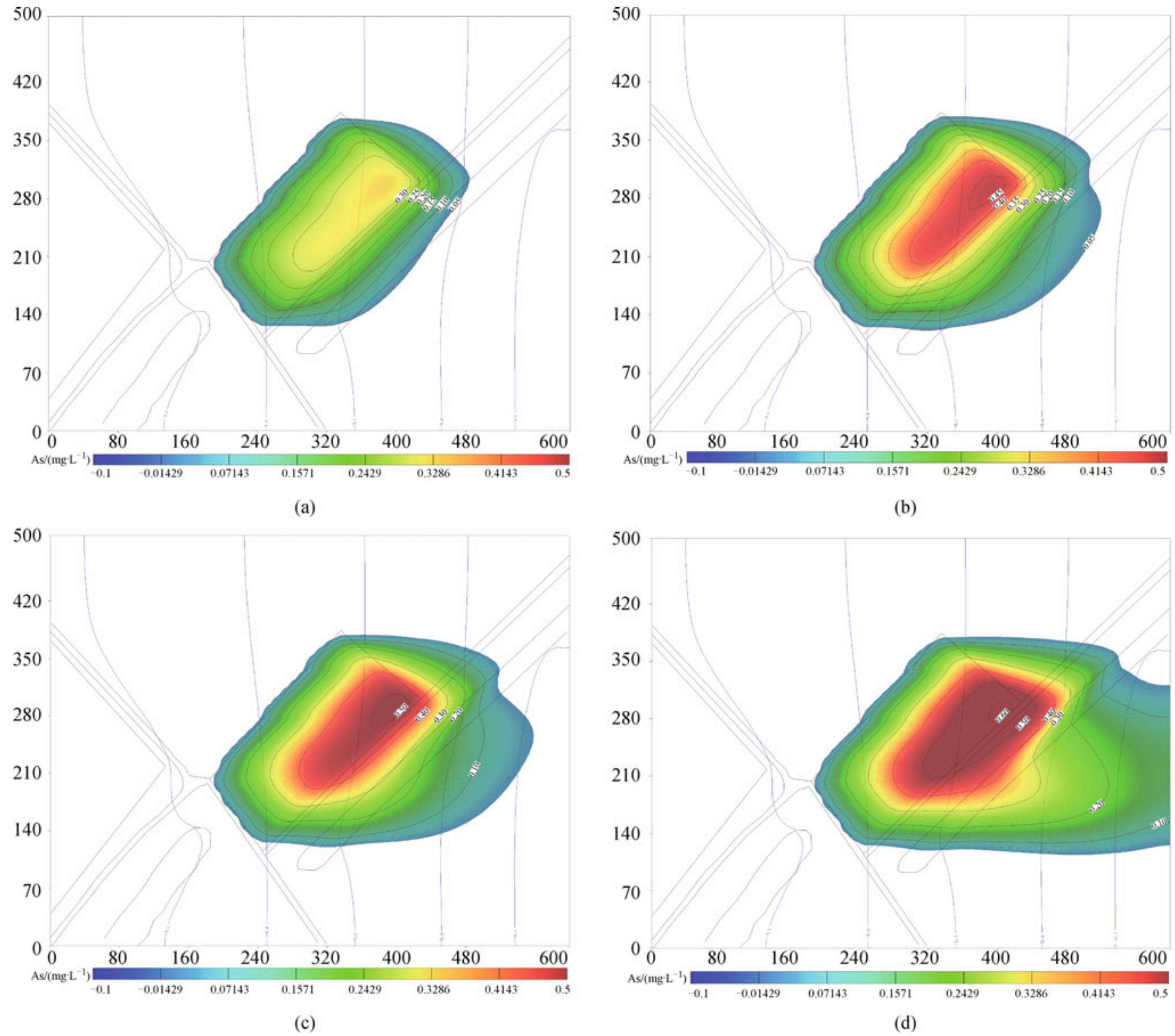
Fig. 2 Match of the observed and calculated (a) groundwater level and (b) arsenic concentration.

constantly extend and diffuse along flow direction to the downstream, and arsenic concentration was to gradually decrease with the increasing transport distance, as shown in Figs. 3(a)–3(d).

In the initial simulation period of five years, the area that arsenic concentration exceeded the 3rd level standard of quality standard for groundwater (GB/T14848–1993) would be small and primarily centralize within the landfill. In the simulation period of eight years, the longest lateral and longitudinal distance of the plume was to reach 200 m and 260 m, respectively, and the central region concentration of the arsenic plume was to rapidly increase. However, the area of high concentration region of arsenic was not to obviously increase from the eight years to the ten years. The main reason might be that the downstream river and the pumping well in the farmland had a capture function to the plume, which had confined diffusing speed and scope of the plume; in the simulation period of twenty years, the scope of the arsenic contamination was to overpass the boundary of the landfill and spread to the downstream river and the farmland region. Moreover, the scope of the arsenic plume was to more obviously be extended, which revealed that the capture function of the downstream river and the pumping well was limited within an extent time range.

3.2 The effects of remedial alternatives

In order to protect the groundwater in the vicinity of the landfill, controlling pollutant source has been widely used. It contains source reducing and pollution pathway cutting-off (Reinhart et al., 2002). Source reduction mainly



(a)

(b)

(c)

(d)

Fig. 3 Tendency of arsenic transport in the water-table aquifer for (a) five years, (b) eight years, (c) ten years and (d) 20 years.

contains removing source and hardening ground. For pollution pathway cutting-off, there are several alternatives. For example, leaking-proof barriers, pumping wells and drainage ditches, etc. (Zheng et al., 1991; Dai and Yu, 2003; Zheng and Bennett, 2009; Zhang et al., 2010b). However, as far as unregulated landfills are concerned, adopting source reducing is to spend a heavy workload and a large cost. So, in the study pollution pathway cutting-off was selected as the primary remedial method. Based on the above established groundwater flow and solute coupled model, five groundwater remedial alternatives were conducted to restrict the plume diffusion.

3.2.1 Hardening ground

Groundwater system may be changed by hardening ground. It makes the aeration zone structure from three layers to four layers (harden zone, soil water zone, immediate vadose zone and capillary water zone, respectively). The harden zone can make coefficient of surface runoff increased. Ordinarily, the coefficient value was 0.9 (Wang, 2004; Cheng et al., 2006). It means that 90% of the rainfall would form surface runoff. So recharge rate for leachate was to be reduced. The effect of the remedial alternative was shown in Fig. 4.

By contrasting Fig. 4 with Fig. 3(b), it was shown that arsenic concentration was largely lower than under no hardening ground after hardening ground for eight years. Under the condition of no hardening ground, arsenic concentration of each point of the plume was almost to exceed 0.05 mg/L, indicating that the groundwater had lost drinking function. But, by hardening ground arsenic concentration of outer-ring and central part of the plume in the groundwater would be close to 0.01 mg/L and 0.05 mg/L, respectively. Furthermore, the contaminant transport rate was obviously changed. Under the condition of no hardening ground the arsenic plume was to spread to the pumping well in the downstream farmland region after eight years. By contrast, under the condition of hardening ground, the plume was to only partly reach the downstream river border after eight years. Therefore, it was indicated that hardening ground was a very important remedial method for unregulated landfills.

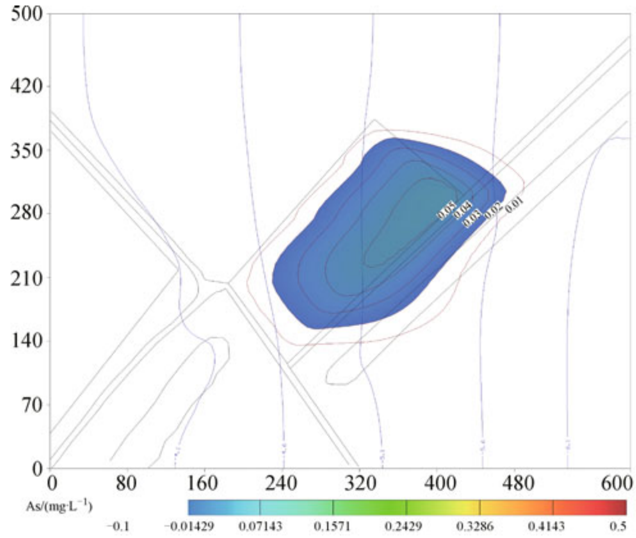


Fig. 4 Tendency of arsenic transport by hardening ground after eight years.

3.2.2 Pumping wells

Pumping wells can speedily change flow speed and direction. Therefore, there is a rapid response to groundwater contamination. Meanwhile, the operation of adjusting pumping time and discharge rate of pumping wells is relatively flexible to control the plume diffusion scope. Considering that the purpose of installing pumping wells was for cutting off the pollution pathway, in the study the pumping well location was installed in the downstream of the plume. According to the plume diffusion scope and arsenic concentration, discharge rate of the pumping well was determined as 100 m^3/d, 200 m^3/d, and 300 m^3/d for testing the capturing effect of the pumping well. The pumping time was determined as ten years and twenty years, respectively, as shown in Figs. 5(a)–5(f).

By contrasting Figs. 5(a)–5(f) with Figs. 3(c) and 3(d), it was shown that under the condition that discharge rates of 200 m^3/d and 300 m^3/d, the arsenic plume diffusion was effectively restrained; while the discharge rate was more than 200 m^3/d (e.g., 300 m^3/d), the plume shape was similar to that of 200 m^3/d, merely the diffusion speed was to be brought forward to achieve the steady state, and the plume scope was not to be obviously diminished after reaching the steady-state. In addition, considering remedial cost, the discharge rate of 200 m^3/d could be enough to satisfy the demand of effectively controlling the plume diffusion.

3.2.3 Leakage-proof barriers

Leakage-proof barrier is that by curtain grouting to construct a barrier which can cut off contaminant transport pathway and change contaminant transport direction to control further contamination diffusion. In the study, suspending the leakage-proof barrier was installed between monitoring well of arsenic concentration and the landfill. The width of the leakage-proof barrier was set as 500 m. The permeable coefficient of leakage-proof barrier was set as 1×10^{-9} m/s and the thickness was set as one meter (Xie, 2009). The remedial alternative was conducted for ten years and twenty years, respectively, as shown in Figs. 6(a) and 6(b).

By contrasting Figs. 6(a) and 6(b) with Figs. 3(c) and 3(d), it was shown that arsenic transport distance was

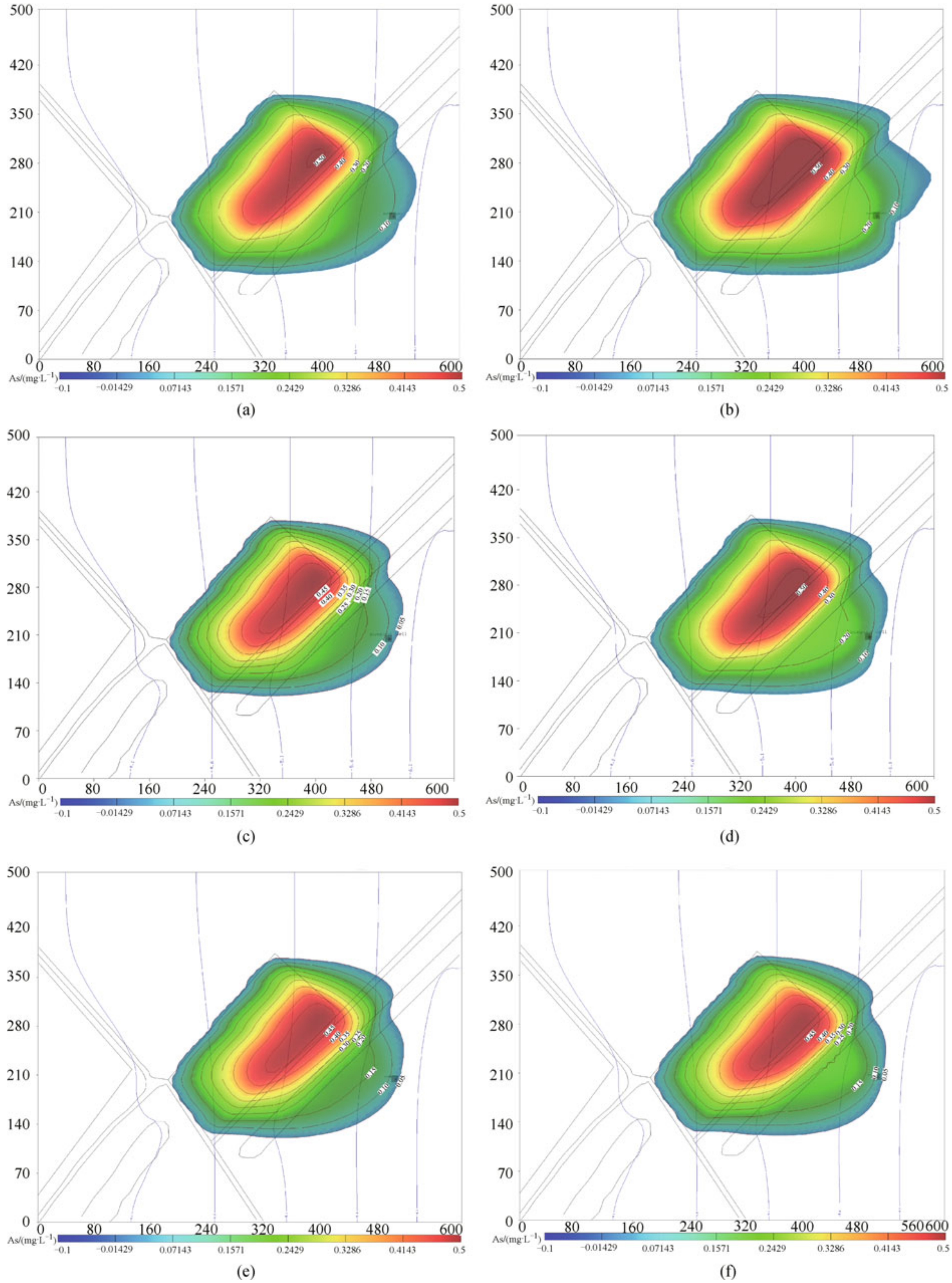
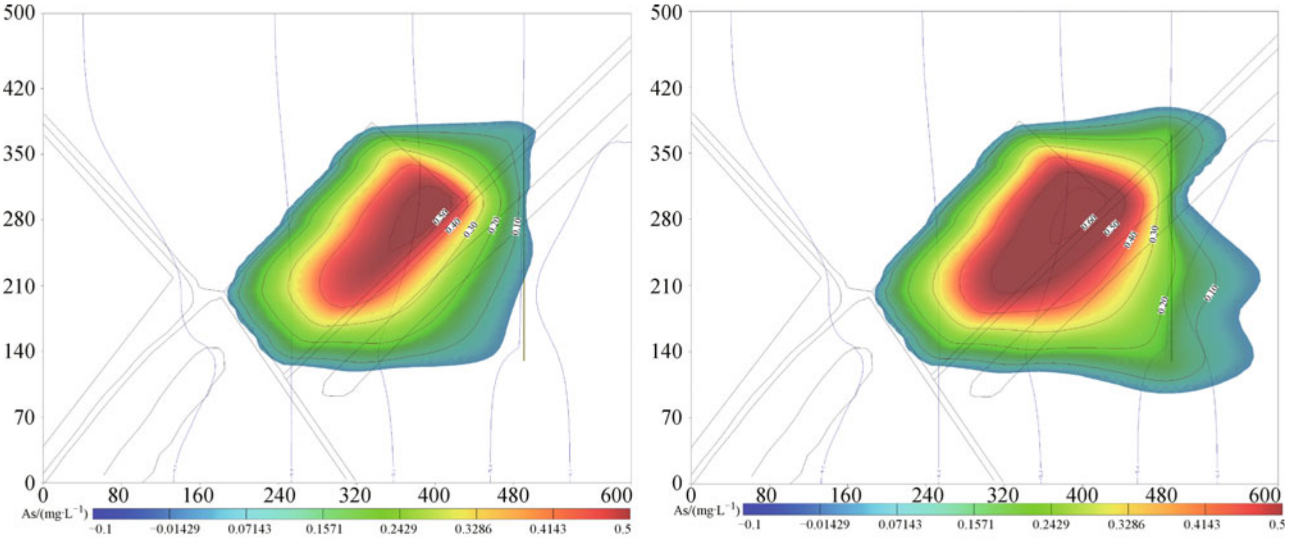


Fig. 5 The remedial effect of the arsenic plume under the pumping well's discharge rate of 100 $m^3 \cdot d^{-1}$ and pumping time of (a) ten years and (b) 20 years, 200 $m^3 \cdot d^{-1}$ and pumping time of (c) ten years and (d) 20 years and 300 $m^3 \cdot d^{-1}$ and pumping time of (e) ten years and (f) 20 years.



(a) (b)

Fig. 6 Tendency of the arsenic transport by installing leakage-proof barrier for (a) ten years and (b) 20 years.

shorter than under no leakage-proof barrier. However, the plume was to circle the leakage-proof barrier and further to contaminate the groundwater of the sensitive object after twenty years. Therefore, within an extent time range leakage-proof barriers might effectively protect the groundwater of sensitive objects. But for the continuous point source, with time increasing the remedial effect of the leakage-proof barrier was not satisfying.

3.2.4 Drainage ditches

Drainage ditches is that by draining the contaminated groundwater to achieve reducing the total quantity of contaminants and controlling the plume. The drained groundwater after treatment may be recharged into aquifers or be used in other ways. In the study, the drainage ditches were installed between the landfill and the farmland. The length was 80m, the depth was 3 m and the water depth of drainage was kept at 0.5 m. By applying the DRN program package of Visual Modflow, the impact of contaminant transport was simulated after installing the drainage ditches' twenty years, as shown in Fig. 7.

By contrasting Fig. 7 with Fig. 3(d), it was shown that arsenic diffusion scope was to largely shrink after installing the drainage ditches. But the plume was to overpass the drainage ditches after 20 years. It indicated that installing drainage ditches had a better effect to control groundwater contamination of the landfill within an extent time range.

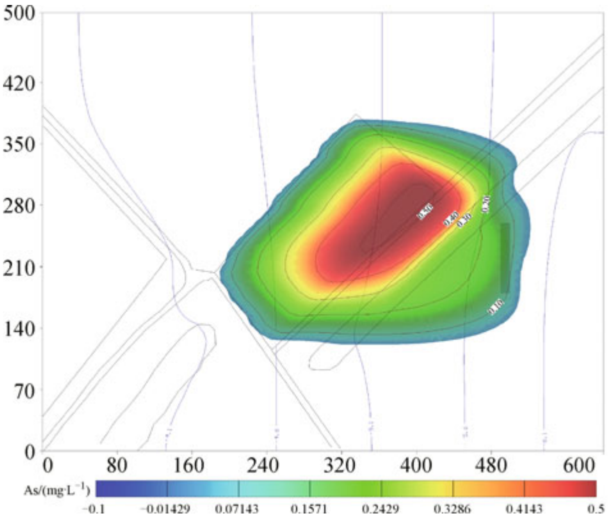


Fig. 7 Tendency of the arsenic plume transport by installing the 80m length drainage ditch after 20 years.

3.2.5 Combining ground-harden with drainage ditches

Analysis of the above four remedial alternatives indicated that each of them had its limitations. Hardening ground could reduce contaminants levels in the groundwater by controlling rainfall permeation, but long-term rainfall permeation was still a main recharge way for groundwater contamination, so the remedial method was not a long and far plan; leakage-proof barrier could change the direction of contaminant transport by cutting off the plume to protect downstream sensitive objects, but total amount of contaminant could not still be reduced; pumping wells and drainage ditches could reduce the contaminant amount by discharging, but the cost for treating contaminated groundwater in the later period was to be largely increased. Considering the above issues, the alternative combining hardening ground with drainage ditches was designed as a comprehensive remedial method to control the landfill-

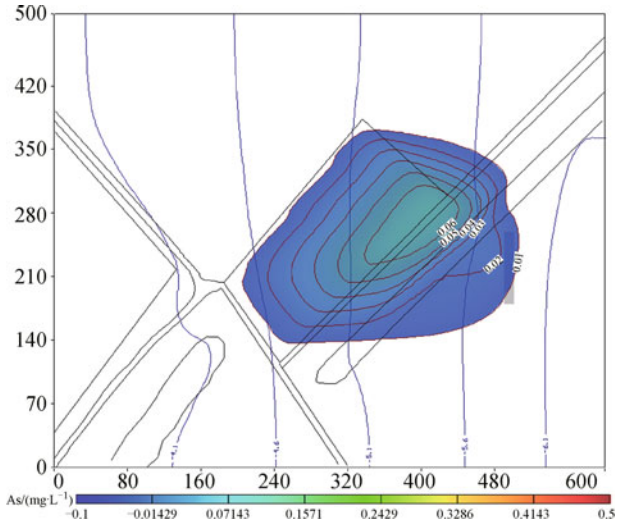


Fig. 8 Remedial effect of optimized method by combining ground harden with drainage ditches after 20 years.

leachate contaminated groundwater.

By contrasting Fig. 8 with Fig. 3(d), it was shown that the plume scope was to centralize around the landfill and still wasn't to reach the farmland region after applying the combined remedial alternative for twenty years. Meanwhile, due to ground harden, the amount of leachate and recharge rate of rainfall were largely reduced, and the amount of draining water were to be obviously reduced from 170.26 m^3/d to 111.43 m^3/d and that a cost for treatment was to decrease. It was indicated that the effect of the combined remedial method was superior to a single remedial method.

4 Conclusions and suggestion

After the leachate of the unregulated landfill permeated into aquifers, arsenic was to be transported along groundwater flow direction, and the plume scope was constantly expanded with prolonged time. As discharge units, the downstream river and pumping well in farmland had a capture function for arsenic contamination. It could make the arsenic transport rate and the arsenic plume scope restricted within an extent time range.

For hardening ground, leakage-proof barrier, pumping well and drainage ditch, the four kinds of remedial alternatives had good effects for controlling groundwater contamination of unregulated municipal solid waste landfills. But there were still some limitations. For hardening ground, by lessening coefficient of rainfall infiltration, to control the plume diffusion, but the total amount of contaminants were not to be decreased; for pumping wells, according to the plume diffusion scope and contaminant concentration, a reasonable discharge rate of the pumping well was determined, it could effectively control the plume diffusion, but the remedial cost was relatively higher; for leakage-proof barriers, within an extent time range it might effectively protect groundwater of sensitive objects, but for the continuous point source, the plume was still to circle the leakage-proof barrier to contaminate the downstream groundwater with the prolonged time; for drainage ditches, there was a better remedial effect for groundwater contamination, however, the remedial alternative couldn't control contamination from the source, but also it was to make a big amount of discharged water, which was to lead to take a high cost for treatment.

The comprehensive alternative combining ground-harden with drainage ditches is considered as the most suitable remedial alternative for unregulated landfills than anyone single remedial method. It can achieve controlling groundwater contamination and reduce total discharging amount per day of drainage ditches. It is profitable for final treatment of contaminants. Therefore, it is suggested that the comprehensive remedial alternative should be used when leachate leakage has happened in unregulated landfills.

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