Evaluation of groundwater remediation strategies at petroleum contaminated sites based on groundwater modelling approach

L H Yang1,2, L X Jing3,5, and C M Zheng4

1Water Science Research Center, Peking University, Beijing 100871, China
2State Environmental Protection Engineering Center for Industrial Contaminated Site and Groundwater Remediation, Beijing 100082, China
3Environmental Planning Institute of Environmental Protection Department, Beijing 100012, China
4School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China

Email: jinglx@caep.org.cn

Abstract. Based on the hydrogeological survey and groundwater environmental investigation at an abandoned oil refinery factory, a site-specific groundwater flow and solute transport model was constructed to support the development of groundwater remediation strategy. The contamination plume of Benzene is simulated and predicted in 30-year scale for designed scenarios. The results indicate that the groundwater quality takes long time to recover even though the contamination source above the water table is cleaned up. This is due to the large quantity of solved contaminants in local aquifer, and additionally the contribution from groundwater circulation is limited. The groundwater remediation actions, such as Pump & Treat (P&T) and In-Situ Chemical Oxidation (ISCO) could greatly improve the groundwater quality. However, under the site-specific circumstance, the ISCO technique is efficient but costly; the P&T takes longer time but more flexible and effective in protecting target drinking wells. Therefore, a combined remediation approach including both P&T and ISCO would be recommended. In summary, by the quantitative analysis regarding the feasibility, time scale, and effectiveness for the potential applicable remediation approaches, the groundwater modelling framework provided a insight on the system behavior and reliable support for the decision making in groundwater protection.

1. Introduction

Under the framework of Twelfth Five-Year Plan of Ministry of Environment Protection of China, a general groundwater contamination survey was conducted nationwide since 2011. According to the survey results, petroleum industry, as one of the major contamination sources, have drawn growing attention since its impaired environmental impacts on soil and groundwater is increasingly widespread. Petroleum-product leakage and spill in factory fields, storage tanks, transmission pipes, and site of accident led to numerous soil and groundwater contamination [1,2]. The contamination can pose a variety of impacts and risks to communities, including human health and ecosystem. Consequently, it is desired to develop remediation strategies and management alternatives with sound environmental and socio-economic efficiency.

The fate and transport process of petroleum products in subsurface is related to a number of physical and biogeochemical transport processes [3]. Therefore, when decisions regarding site
remediation are to be made, integrated consideration that incorporates these processes within a general framework rather than examining them in isolation would be useful for generating effective cleaning-up alternatives. The groundwater modelling is an efficient and practical approach to support remediation strategies development by simulating the multiple processes simultaneously, predicting various scenarios, and evaluating the proposed remediation strategies [4-6]. The standard model tools identified by USEPA for groundwater flow and contaminant transport modelling includes: MODFLOW [7], the most classic groundwater flow model, and MT3DMS [8], which is fully coupled with MODFLOW and simulates groundwater solute advection-dispersion and multiple biogeochemical processes.

This work focuses on the feasibility study of various groundwater remediation technologies at a specific petroleum products contamination site based on combined groundwater modelling approach. In this case study, the proposed remediation alternatives include Pump & Treat (P&T), In-Situ Chemical Oxidation (ISCO), and natural attenuation. The feasibility of the remediation technology was evaluated, with its duration, efficiency, and effectiveness on protecting the potential receptors. In addition, the comprehensive comparison between proposed alternatives could improve the understanding for the site characteristics and contaminant transport processes, which support the environmental management agency to make proper decisions. The modelling approach could help petroleum industries to reduce costs at consulting, planning, designing, and operation stages of their remediation practices, and protect human health and ecosystem in a more efficient and precise way.

2. Overview of the study site
The study site is located on a loess plateau in northwest of China (Figure 1). The site was operated as an oil refinement factory established in 1970's and closed in 2010. The factory complex is distributed on the eroded first terrace of Huan River, a major local river running from northwest toward southeast, and deeply cutting through the loess layer and reaches the bedrock in the river bed. The flow rate of Huan River is averaged to 3.3m³/s. The averaged local annual precipitation is 521 mm. The natural terrain slope is around 6‰, with the direction from loess terrace on the bank side towards river channel.

![Figure 1. Map of study area.](image-url)
According to the site investigation in 2016, both soil and groundwater in the factory complex was contaminated due to leaching from an aboveground storage pond and accident spill in the operation history. At the sampling location that close to the major contamination spots, the vertical soil profile shows visible contaminant residues in the top soil and deeper sandy gravel layers. The concentration of dissolved total petroleum hydrocarbon, benzene, and toluene in the groundwater has greatly exceeded the local groundwater quality guidelines. The contamination plume kept spreading out with groundwater flow.

Since the water quality of surface water is in poor condition, the local municipal water supply relies on the groundwater. The residents in the vicinal villages (Figure 1) pump groundwater from their private wells for drinking water and daily uses. Apparently, the human health of local residents who live close to the contamination plume potentially expose to the groundwater contamination. In addition, because of the hydraulic connection between aquifer and surface waterbody, the river reach of Huan River and its tributary Xin Creek close to the site become another potential contamination receptor. Therefore, remediation action is required by local environmental protection agency to protect the public health and for the future land development.

3. Methodology

3.1. Conceptual model

3.1.1. Model domain. The hydrogeological survey reveals that the local phreatic aquifer mainly makes of Quaternary silt and sandy gravel, underlying a mudstone aquitard, which separates the phreatic aquifer from the deeper confined aquifer. The thickness of the phreatic aquifer ranges from 3m to 15m, and the depth of water table ranges from 2m to 10m, with an average of 7m. Following the natural topography, the phreatic aquifer extends from the loess tableland in the northeast toward west and south. Groundwater eventually drains into Huan River and its tributary Xin Creek (Figure 1). Therefore, the boundary condition is conceptualized as general head boundary in the east and southeast. The west boundary is the river, set as constant head and the input data are based on the monitored river stage height. The total area within model domain is 2.3 km².

The source terms of groundwater in the study area are infiltration of precipitation and horizontal recharge from the loess layer in the east. The sink terms include river discharge and local well pumping. Regarding the long-term water level monitoring record, the flow pattern in the study area is quite stable. In summary of the above information, the study aquifer is conceptualized as a one layer heterogeneous aquifer with two-dimensional steady state flow pattern.

3.1.2. Contamination source, transport pathway and receptors. The site investigation indicates that there are two groundwater contamination source areas. The major groundwater contamination source is the aboveground storage pond located in the middle of site (Figure 2). The waste water without treatment was stored in the pond. The size of the pond is 50m × 60m. Since the storage pond did not install seepage-proofing liner on the bottom, waste water contains petroleum products leak from the pond bottom, transport through unsaturated zone, and reach the water table underneath. Various contaminants then spread out along with the groundwater flow.

Another contamination source is located in the southeast of site. The contamination was caused by the spill accident in the operation history (Figure 2). The contaminant residues in the top soil layer transport into aquifer with the infiltration of precipitation.

The receptors of groundwater contamination include both local residents who use the groundwater and the surface waterbody, i.e. Huan River and Xin Creek. The contaminant discharge to the river will pose risks to the river ecosystem.
3.1.3. Fate and transports of target contaminant. Groundwater environmental investigation indicates that the site contaminant of concern is total petroleum hydrocarbon (TPH). The representative constituent of TPH is Benzene because of its toxicity for human health. Thus, Benzene is determined as the target contaminant for remediation clean-up. The fate and transport processes of Benzene under different clean-up technologies application will be simulated and evaluated using combined groundwater modelling framework. According to the property of benzene, its transport processes include advection, dispersion, absorption and biodegradation. The physical transport processes are dominated by groundwater flow pattern. The reaction processes depend on the geochemical condition in the aquifer.

![Figure 2. Map of contamination plume (Benzene).](image)

3.2. Numerical model construction

3.2.1. Flow model. To transfer the conceptual model into a numerical model, the first step is spatial discretization. The hydrogeological unit in the model domain is divided into 29443 grids with the grid size 10m × 10m. In the contamination source area and vicinity, the model grids are refined to 5m × 5m (Figure 3). Surface and bottom elevation are defined using local DEM data and borehole records.

The groundwater flow pattern is simulated using MODFLOW [7]. The input data for the general boundary head in the east is estimated based on the Darcy’s Law, including the water level in the loess layer and conductance of the flow pathway. The recharge rate is calculated with local precipitation record and infiltration rate from the regional study. The overall pumping rate, estimated from the number of local residents and the averaged daily water usage. The hydraulic conductivity derived from the local hydrogeological survey report, the initial value was set to 0.8-1.5 m/d, and adjusted in the calibration process.
The flow model is calibrated using the monitoring data from 30 monitoring wells in the study area. The comparison between calculated and observed water level shows well agreement between model and reality (Figure 4(b)). The simulated steady state flow pattern is shown in the Figure 4(a).

Besides the calibration base on water level observation, the system water balance is analyzed to confirm the boundary condition and source & sink set-up are reasonable. The flow-in and flow-out items and their partitions is listed in the Table 1. The water balance analysis indicates that the recharge from precipitation and horizontal flow from loess layer in east boundary count for 47.9% and 52.1% of total inflow respectively. The main discharge terms are river discharge (including both Huan River and Xin Creek) and pumping, counting for 65.5% and 30.2% respectively. This result implies that the river and local residents would be the potential contamination receptors.
Table 1. The water balance analysis in the modelling system.

| Inflow Items                        | Flow Rate (10^4 m^3/a) | Percentage (%) | Outflow Items                        | Flow Rate (10^4 m^3/a) | Percentage (%) |
|-------------------------------------|------------------------|-----------------|--------------------------------------|------------------------|-----------------|
| Horizontal flow from loess layer    | 3.10                   | 52.1            | Discharge to Huan River              | 2.93                   | 49.2            |
| Precipitation recharge              | 2.86                   | 47.9            | Discharge to Xin Creek               | 0.97                   | 16.3            |
|                                    |                        |                 | Pumping                              | 1.80                   | 30.2            |
|                                    |                        |                 | Discharge to the south boundary      | 0.26                   | 4.3             |
| Sum                                 | 5.96                   | 100             | Sum                                  | 5.96                   | 100             |

3.2.2. Transport model. Based on calibrated flow pattern, the MT3DMS model was applied to simulate the multiple transport processes of Benzene in the aquifer. For the contamination source at waste water storage pond, the model source loading was assigned to grids where the waste water storage pond is located. For the contamination source at the spill spot, the model source loading was assigned to the center area where soil was contaminated.

The boundary condition is set as flux boundary condition. The inflow boundary is zero since the samples took from upstream background well indicate that there is no Benzene mass input from outside. The mass loss through outflow boundary is calculated with model. The initial concentration in the rest area is based on the concentration contour map of Benzene (Figure 2).

It was assumed that: (1) recharge from precipitation remains constant over time; (2) hydrodynamic conditions are steady state and equal to those observed in current condition; (3) the contaminant loading remains constant concentration over time since the large quantity of contaminant in the source and dissolution process remains equilibrium. We took the current concentration level as the recharge concentration (as shown in Figure 2).

3.2.3 Design of remediation scenario. Regarding the situation in this contamination site, a number of remediation techniques are potentially applicable to clean up the contaminated soil and groundwater [9,10]. In this study, the combined groundwater numerical modelling framework is used to better understand the system behavior and then support the decision making process during remediation strategy development. Each remediation plan is designed as a simulation scenario based on the differences of contaminants loading, hydraulic pattern and reaction conditions. The predictive model results then are used to examine the performance of each remediation technologies under various conditions, including issues of system configuration, process operation, treatment efficiency and cost. The details of remediation scenario design are as described below.

S1: Baseline
In baseline scenario, the site leaves in the current situation and does not implement any clean-up practice. In theory, the processes that Benzene leaving the system include discharge to surface water and natural attenuation; the process that Benzene entering the system will be recharge from source area. Therefore, the MT3DMS simulates advection, dispersion and natural attenuation processes.

S2: Source Clean-up
In S2 scenario, the remediation plan is to clean up the contamination source, i.e. remove the aboveground storage pond and excavate contaminated soil, but no further groundwater clean-up action. In this scenario, the source loading is set up as transient recharge concentration, i.e. the recharge concentration at the starting time takes the current value based on the site investigation results, and in the rest of the simulation time, assuming no mass loading to the system, the recharge concentration is set to zero.
S3: Source Clean-Up and Pump & Treat (P&T)
In S3 scenario, the remediation plan is to clean up the contamination source first and then implement Pump and Treat (P&T) remediation. P&T extracts the contaminated water from the aquifer and treat it ex-situ prior to discharge [11]. For the source area centered with the aboveground storage pond, pumping wells are installed in the central area of the plume. For the source area caused by spill accident, the pumping wells are installed in the central area and on the pathway between source area and private pumping wells. The purpose of P&T is to extract contaminants mass out of aquifer while reduce the area of plume. The pumping wells change the local flow pattern to avoid private pumping well capturing the plume.

S4: Source Clean-Up and In-Situ Chemical Oxidation (ISCO)
In S4 scenario, the remediation plan is to clean up the contamination source first and then implement In-Situ Chemical Oxidation (ISCO) technology, which introduce the chemical oxidant (e.g. hydrogen peroxide, activated sodium persulfate, or sodium persulfate into subsurface to enhance the attenuation of organic contaminant [12]. In ISCO remediation system, construct injection wells in the plume area, inject selected oxidant to the aquifer through wells.

3.2.4 Transport Parameter. In summary, all scenarios simulate the physical transport processes (i.e. advection and dispersion) and biogeochemical process. Biogeochemical processes including absorption and biological degradation. The absorption process is assumed as linear isothermal adsorption. The biological degradation process is simulated as the first order reaction.

Transport parameter are determined based on the borehole log analysis and literature studies [13,14]. The parameters related with physical transport process, such as effective porosity and bulk density, are from the field geological survey report. The longitudinal dispersivity is estimated regarding the size of model domain. The reaction parameters are from the literatures that conducted the experiments or pilot tests focusing on the Benzene transport issues in similar sites and remediation actions [15-17]. Distribution coefficient is required for the simulation of absorption process. First order reaction rate are set up in natural condition (scenario S1, S2 and S3) and enhanced degradation condition (scenario S4) respectively. Transport model parameters are listed in Table 2.

| Parameters                                           | Values   | Units       | Source                                           |
|------------------------------------------------------|----------|-------------|--------------------------------------------------|
| Hydraulic conductivity                               | 0.52~1.5 | m/d         | based on calibrated flow model                   |
| Effective porosity                                   | 0.2      | -           | local hydrogeological survey report              |
| Longitudinal dispersivity                            | 10       | m           | empirical value based on site scale (Zheng et al., 2010) |
| Ratio of horizontal transverse dispersivity and longitudinal dispersivity | 0.1      | -           | empirical value based on site scale (Zheng and Wang, 2002) |
| Ratio of vertical transverse dispersivity and longitudinal dispersivity | 0.01     | -           | empirical value based on site scale (Zheng and Wang, 2002) |
| Bulk density                                         | 2000     | kg/m³       | local hydrogeological survey report              |
| Distribution coefficient (Sorption)                 | 0.06     | mL/g        | literature (Liu et al., 2006)                    |
| First-order irreversible kinetic reaction rate (dissolved phase) | 0.005   | d⁻¹         | literature (Monica et al., 2004)                 |
| First-order irreversible kinetic reaction rate (sorbed phase) | 0.005   | d⁻¹         | literature (Fan et al., 2014)                    |

4. Results and discussion

4.1. Predictive results
S1: Baseline
The predictive simulation of baseline reveals that if the site stays in present condition without any clean-up action, the system Benzene mass loading from leaching is greater than the mass losing via attenuation and discharge, therefore the plumes will slightly extend toward the downstream (Figure 5). However, due to the low permeability of porous media and low hydraulic gradient in the study area, the expand of plume is limited. This result indicates that the trend of contamination in groundwater will keep increasing for a long term but spatial distribution won’t have significant increase.

S2: Source Clean-up
The prediction result of scenario S2 indicates that even though the source has been removed and no mass loading to the system anymore, the spatial distribution of plume keeps the similar extention with scenario S1 (Figure 5). The total mass in the system is slowly reducing through discharging to surface water and natural attenuation. If there is no further remediation action after source clean-up, the impair impact of the groundwater contamination on the local drinking water supple and surface water quality will last for a relatively long period time (over 100 years).

![Figure 5. Comparison of predicted contamination plume for scenario S1 and S2.](image)

S3: Source Clean-Up and Pump & Treat
The scenario S3 has the same initial condition with scenario S2. During the simulation period, there is no mass loading. The contaminants leave the system mainly through P&T, instead of discharge and natural attenuation. The important issue of implementing the P&T remediation is to optimize the pumping rate and pumping well locations in order to maximize the efficiency of mass removal, reduce the plume and protect the potential receptors in the area. In this study, the pumping rate is set to the allowed maximum value regarding the local aquifer test. For the plume centered on the waste water
storage pond, the pumping wells are installed at the center of plume and on the pathway that contaminant transport from source to Huan River. For the plume centered on the accident spill, install pumping wells on the pathway between the source area and the private pumping wells nearby (well ID C11, C22 and C27 (see Figure 6(a))).

Figure 6. (a) Map of initial plume and the location of nearby private pumping wells; (b) – (e) the breakthrough curve at each private plumping well.

The simulation result of scenario S3 indicates that the Benzene plume is gradually shrinking with the P&T remediation (Figure 7). Around ten years later, the plume extension defined by contour line for drinking water standard of Benzene (10μg/L) will exclude the private pumping wells located
nearby, i.e. the Benzene concentration in private pumping well will decrease to less than 10μg/L and meet the drinking water standard. Since the pumping rate is limited by the low permeability, the remediation time to attain the water quality standard is relatively long.

**S4: Source Clean-Up and In-Situ Chemical Oxidation**

The scenario S4 also set as the same initial condition with scenario S2. In S4 scenario, assuming that oxidant chemicals are injected into the aquifer where Benzene concentration is greater than drinking water standard and fully mixed with groundwater, the degradation process then is accelerated with greater reaction rate than natural attenuation process. The simulation result indicates that the enhanced degradation process eliminate the Benzene in aquifer with high efficiency. The concentration level of Benzene drops down to the drinking water standard 150 days later (Figure 7). After 500 days, the Benzene concentration almost in the entire study area decreases to less than 10μg/L and meet drinking water standard.

![Figure 7. Comparison of predicted contamination plume for scenario S3 and S4.](image)

4.2. *Screening of remediation technologies*

**Efficiency of contaminant removal**

For comparison, the temporal trend of total mass change rate in each scenario is shown in Figure 8. The predictive results of scenario S1 and S2 shows that source clean-up will not significantly effect the spatial distribution of plume, but the concentration level in the center area will keep increasing if the contaminants keep leaching from the source. Both P&T and ISCO can eliminate the total mass of benzene in the aquifer. Because of low permeability, the efficiency of P&T approach is limited. However, for the purpose of private well protection, P&T could alter the local hydraulic pattern and better capture the plume. ISCO approach will greatly enhance the degradation of Benzene, but since
the low permeability, the difficulty of deliver oxidizing agent to the target zone will be a concern in practice.

![Figure 8. Total mass change rate of Benzene in each scenario](image)

**Impact assessment for contamination receptor**

In order to better evaluate the impact of contamination on local residents, the concentration trend in four pumping wells that initially located within the plume were studied (Figure 6). ISCO has the best remediation efficiency. The breakthrough curves in all scenarios indicate that Benzene concentration decreases significantly once the ISCO remediation starts. The P&T impacts differently for wells depending on location. Well C26 is located downstream of groundwater flow direction, and not close to any remediation pumping wells, the concentration trend is scenario S1, S2 and S3 has no significant difference. Well C11 is located near the contamination source center, showing the decreasing trend for all scenarios. C22 and C27 are located in the downstream of groundwater flow direction. The concentration at these two wells keep increasing in S1 and S2 due to the mass flux comes from the source area in upstream. In S3, the pumping wells alter the local flow pattern and capture the plume toward the source area direction, the concentration in these two wells start to decrease. These results reveal that even though the pumping rate is limited since low permeability, the optimized pumping well location works efficiently for plume capture.

5. Conclusion

In this study, the combined groundwater flow and transport model are applied for the development of groundwater remediation strategy. Four simulation scenarios represent the baseline, contamination source clean-up, P&T, and ISCO. Primarily, results of numerical simulation provide detailed spatial distributions of groundwater contamination under each scenario. Furthermore, the predictive simulation assists for better understanding the site conditions and the transport characteristic of target contaminant. The following conclusions are drown to support the decision making.

First, the most important site characteristic revealed by model is the low permeability, which caused the slow hydraulic circulation in the system. Therefore, mass flux to surface water and natural attenuation needs to take long time (greater than 100 years) to eliminate the total mass and reach drinking water standard. The positive groundwater remediation action is necessary in order to protect the local drinking water safety and future land development.

The predictive simulation indicates that both P&T and ISCO are applicable remediation approaches in this site. P&T is relatively less efficient since the pumping rate is limited by the low permeability. However, P&T is flexible and effective for plume capture. ISCO is most efficient for contaminant removal, but very costly and difficult to implement. Because of the low permeability in this site, it’s difficult to delivery oxidant in the aquifer. In order to increase the contact of the oxidant with target
contaminant, either install the injection wells close enough to ensure the radius of influence are overlapping, or implement the fracturing technique to increase the media permeability. Either way is much more costly than P&T technology.

Therefore, the recommended groundwater remediation strategy should be a combined approach including P&T, ISCO and natural attenuation. For the contamination source area, apply ISCO to remove the major portion of the contaminants mass. For the environmental protection targets, such as drinking water pumping wells, apply P&T to effectively capture the plume and avoid contaminant transport into target zone. For the plume distributed in the area where is less important or the contamination level is relatively low, apply monitored natural attenuation to manage the risk.

In summary, a well-constructed groundwater modelling framework can represent aquifer properties, and fate & transport characteristics of contaminants. Modelling approach is a useful tool to better understand the system behavior and provide quantitative analysis results to support decision making. However, there is uncertainty related with model development. Such as the local residents pumping rate needs more detailed data to refine the model inputs. Some transport parameters need field experiments and pilot test to obtain more accurate values. Model could be improved with more monitoring data and experiment results.

Acknowledgments
The research was financed by the National Groundwater Environment Survey and Assessment Project (No.1441100022) and the National Key Research and Development Program (No.2016YFE0102400) of the Ministry of Science and Technology of China.

References
[1] Testa S M and Winegardner D L 1991 Restoration of Petroleum-Contaminated Aquifers (Chelsea, Michigan, USA: Lewis Publishers)
[2] Mohammad H A Z, Freydoon V, Seyed A M and Vahid H 2016 Investigation of petroleum-contaminated groundwater remediation using multi-stage pilot system: physical and biological approach Desalin. Water Treat. 57 9679-89
[3] Logeshwaran P, Megharaj M, Chadalavada S, Bowman M and Naidu R 2018 Petroleum hydrocarbons (ph) in groundwater aquifers: an overview of environmental fate, toxicity, microbial degradation and risk-based remediation approaches Environ. Technol. Innovate. S235218641730264X
[4] Paus L, Ranson D and Koslowsky H P 1995 Mathematical groundwater modelling of industrial sites: A useful tool for environmental monitoring and remediation Contaminated Soil ’95 (Springer Netherlands)
[5] Kiecak A, Malina G, Kret E and Szklarczyk T 2017 Applying numerical modeling for designing strategies of effective groundwater remediation Environ. Earth Sci. 76 248
[6] Prommer H, Barry D A and Davis G B 2000 Numerical modelling for design and evaluation of groundwater remediation schemes Ecol. Model. 128 0-195
[7] Harbaugh AW 2005 MODFLOW-2005, The U.S. Geological Survey modular ground-water model - the ground-water flow process U.S. Geological Survey Techniques and Methods 6-A16
[8] Zheng C and Wang P P 1999 MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide Am. J. Roentgenol. 169 1196-7
[9] Freeman H M and Harris E F 1995 Hazardous Waste Remediation: Innovative Treatment Technologies (Lancaster, Pennsylvania, USA: Technomic Publishing Co., Inc.)
[10] Nyer E K 1998 Groundwater and Soil Remediation: Practical and Strategies (Chelsea, Michigan, USA: Ann Arbor Press)
[11] Cohen R M, Mercer J W, Greenwald R M and Beljin M S 1997 Design Guidelines for Conventional Pump-and-Treat Systems (Ada, Oklahoma: U.S. Environmental Protection Agency)
[12] Siegrist R L, Crimi M, Simpkin T J (eds) 2011 In Situ Chemical Oxidation for Groundwater Remediation (Springer, New York, NY)
[13] Zheng C, Bennett G D and Andrews C B 2010 Analysis of ground-water remedial alternatives at a superfund site Groundwater 29 838-48
[14] Zheng C and Wang P P 2002 A field demonstration of the simulation optimization approach for remediation system design *Ground Water* **40** 258-66

[15] Liu M Z, Chen H H, Hu L Q and He W 2006 Modelling of transformation and transportation of PCE and TCE by biodegradation in shallow groundwater *Earth Sci. Front.* **13** 155-9

[16] Suarez M P and Rifai H S 2004 Modeling natural attenuation of total BTEX and benzene plumes with different kinetics *Ground Water Monit. R.* **24** 53-68

[17] Fan X, He L, Lu H W *et al.* 2014 Environmental and health-risk-induced remediation design for benzene-contaminated groundwater under parameter uncertainty: a case study in Western Canada *Chemosphere* **111** 604-12