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Environmental Contamination and Toxicology

Numerical Modeling for Remediation of Contaminated Land and Groundwater

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In recent decades great effort and research funding have been spent on restoration of contaminated environments. Considerable progress has been made in improving environmental quality but challenges still exist in some areas, such as remediation of contaminated land and groundwater, particularly with impact of urban growth and on-going activities (Kavanaugh 1996; USEPA 1998). To provide sufficient remediation and protection for land and groundwater underneath, minimize environmental risk in infrastructure maintenance and urban re-development in terms of contamination remediation, it is necessary to incorporate understanding of the sub-surface conditions in the decision-making process (Collin and Melloul 2001; Rivett et al. 2002). Characterization of regional and site-specific hydrogeological systems plays an important role in contaminated land and groundwater remediation schemes. Advanced modeling techniques can realize and improve characterization of complex hydrogeological systems (Yang et al. 2003). Numerical models, such as MODFLOW, FEFLOW and MODPATH, provide straightforward approaches for remediation designs. Sophisticated combination of hydrogeologic simulation with mathematical optimization is also a promising method to provide the best design subject to certain constraints (Domenico 1998). Thus, a good understanding and description of the system through numerical modeling is essential for a successful remediation strategy. In this paper, a case study on numerical modeling for remediation of a contaminated site in the dockland area of Dublin, Ireland, is presented. A series of numerical modeling maneuvers were carried out to characterize the contaminated site at three-dimension scale. The models were calibrated with field-monitored data under natural conditions and the calibrated model was used to design a remediation plan using Permeable Reactive Barriers (PRB). A laboratory based feasibility study was also carried forward to study the performance of reactor design of the PRB.

MATERIALS AND METHODS

Remediation of contaminated land and groundwater is becoming a more important environmental issue world wide. Historical urban land-use and industrial activity have resulted in the problem of land contamination, which is detrimental to human

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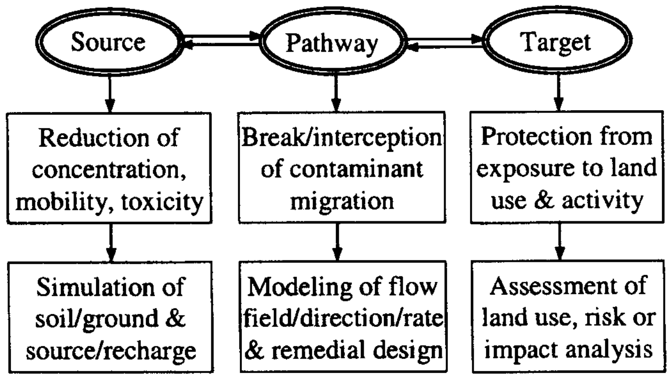


Figure 1. Approach outlining the numerical modeling for risk-based remediation.

life and environment (Fetter 1999). Consequently, shallow groundwater underlying the land is often contaminated in various contents which maybe a means to further carry and spread the contaminants. Effective cleanup of contaminated sites is proving both difficult and expensive and is a balance-keeping process between remediation cost and environmental risk so as to develop suitable and adequate remedies (Kavanaugh 1996; Murphy 2000). The risk of contamination associated with in-situ remediation strategies needs to be assessed at various stages (Al-Yousfi et al. 2000); it may be accordingly ranked for priority according to needs of remediation (Shook and Grantham 1993; Khan and Husain 2001). Risk-based remediation to contaminated land and groundwater is a commonly accepted approach as "source-pathway-targets" to study the risk with consideration of contaminated source, migration pathway of contaminants and final target or receptor for remedial protection (Figure 1). Numerical modeling has been used extensively to understand hydrogeologic systems, characterize contaminated sites and simulate contaminant transport processes (Zheng and Bennet 1995; Domenico and Schwartz 1998; Fetter 1999). Numerical groundwater modeling can be applied to various parts of risk-based remediation methodologies; this approach is outlined in Figure 1.

The numerical groundwater modeling maneuvers were carried out in three strands: regional characterization, zoom-in model in a smaller area; and detailed site-specific study. The regional hydrogeology and groundwater systems were characterized to form a regional conceptual model; a 3-D solid geology and soil model was created based on regional spatial data set. Thus the site characterization was understood in the regional context. A more detailed zoom-in 3-D model was further constructed in the quayside area to simulate the impact of adjacent remedial action and diurnally tidal fluctuation using MODFLOW package. Finally, a site-specific numerical model was built to study the detailed flow field and design the best remediation option. This site model was calibrated with field-monitored data under natural conditions; hydraulic parameters, time-varying river boundary and head-dependant boundary conditions were calibrated to achieve the best fits between modeled and observed groundwater heads. The

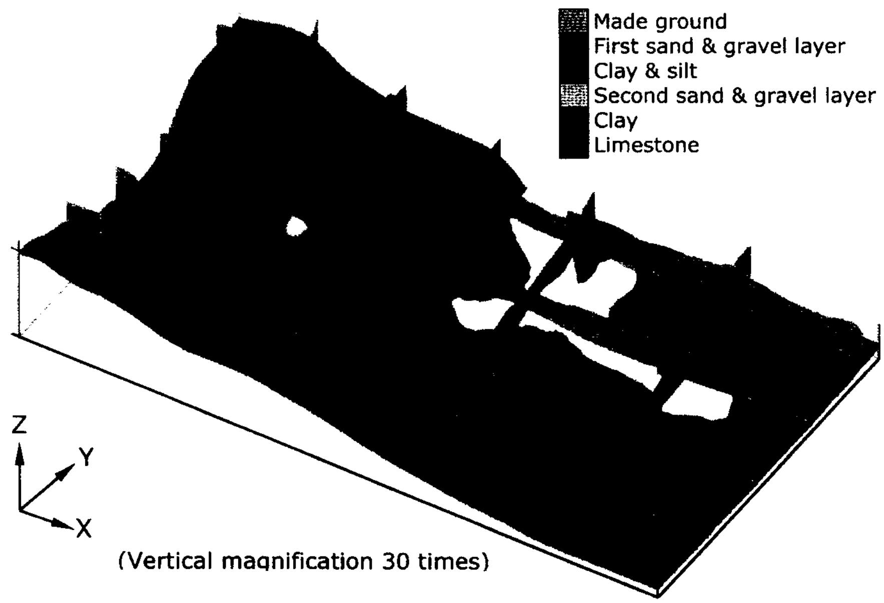


Figure 2. 3-D fence-diagram of the regional area with base of clay and limestone.

calibrated model then was used to carry out a remediation plan design using PRB for both shallow and deep aquifers. The flow fields and paths of the shallow and deep aquifer were predicted with time under various PRB designs (QUESTOR 2002). A laboratory based feasibility study was then carried out to study the performance of reactor design of the PRB. Therefore such modeling exercises have provided sound information for the remediation of the contaminated land and groundwater.

The contaminated site is approximately 2.1 hectares in area and surrounded by the tidal rivers to the north and east, and a canal basin to the south. In the historical development of urban landscape of Dublin, the made ground has been formed successively by infilling depressions and reclaiming foreshore areas for land-use. The site was firstly built for limeworks in the early 1800. It has been used as chemical works and then chemical manure (fertilizers) manufacturers, oilcake mills, alkali manufactures since that time. It was also partly used as stores, storage of oil and general provision, coal yard and warehouse. A company has occupied the site as scrap metal processing yard from 1977 to 1996 (QUESTOR 2002). The preliminary site assessment revealed that the land and shallow groundwater have been contaminated with metals (Zn, Pb, Cu and As), Polyaromatic Hydrocarbons (PAH) and Total Petroleum Hydrocarbons (TPH). The deep groundwater has been invaded by saline water underlying the site. Therefore the environmental impacts of the contamination need to be addressed in relation to public access on the site. To assess the potential risk posed to environmental targets and design the appropriate PRB, a detailed quantitative evaluation of this site is timely needed.

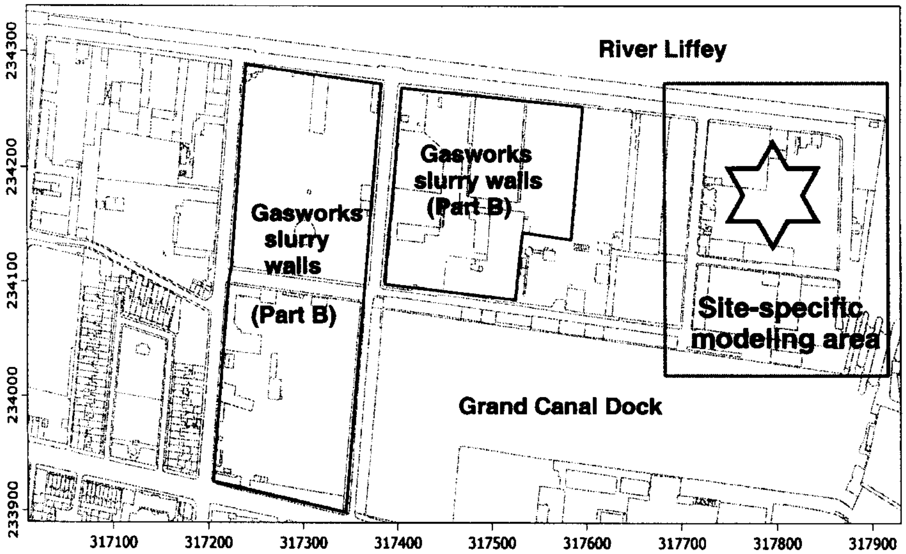


Figure 3. Simulation of the areal model with connection to adjacent remediation.

The Dublin region is underlain by a complex geological sequence. It can be classified as five categories according to the stratigraphic sequence: a) made ground (the anthropogenic alteration of natural tracts of land) and alluvial estuarine clay or silt; b) Glacial and post-glacial gravel and sand; c) Firm/stiff laminated clays; d) Alluvial and glacial sand and gravel; e) glacial till (boulder clays) and limestone hard rock (QUESTOR 2002). The sand and gravel deposits are the aquifer of importance in the regional area, appearing as areas or lenses. A regional borehole database was defined, which was used to create data sets required for 3-D spatial modeling and form a six-layer hydrogeological conceptual model.

RESULTS AND DISCUSSION

The regional study was carried forward by 3-D numerical characterization of the complex solid geology using GMS (EMRL, 2001). The solid model and fence diagrams were created as highly realistically presented images for spatial structure visualization. A typical fence diagram produced is displayed in Figure 2 which shows a clear picture of geology in a regional context. Areal modeling was further carried out to understand the hydraulic responses of the land and groundwater system to human activity in the area covering the contaminated site. This was to identify the relationship between adjacent remediation sites with slurry cut-off wall construction and the study site so as to integrate the regional remedial actions into the remediation strategy at the local site. Figure 3 is a map showing the modeling area of the zoom-in model and location of the adjacent two-phase remediation for land re-development. Part A and B were constructed at different times and were simulated in the transient model runs. The tidal influence

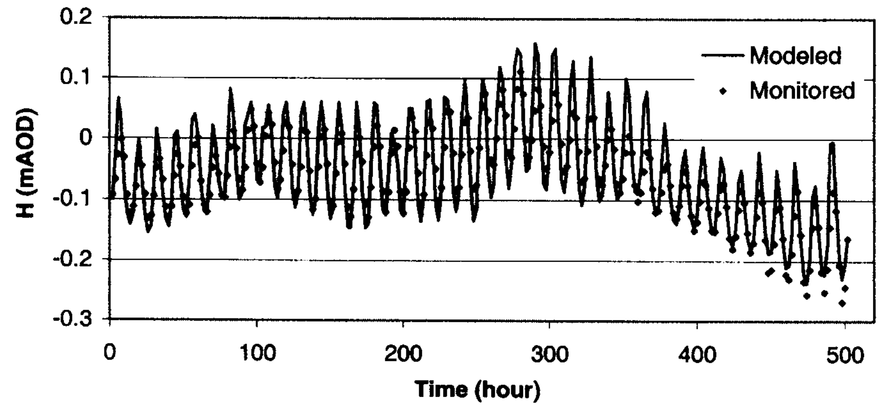


Figure 4. Model calibration matches of typical monitoring well (BH1).

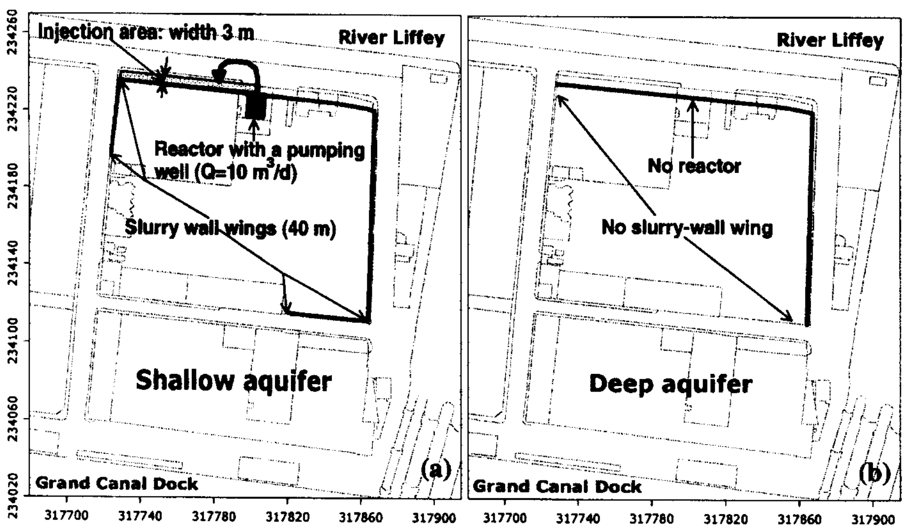


Figure 5. PRB design by the calibrated numerical model, two-aquifer system.

of the rivers on the shallow and deep groundwater fields was also explored with consideration to remediation designs.

The site-specific modeling was a very detailed zoom-in study for simulation of the remediation strategy. The modeling area is within the black box in Figure 3. The numerical model was calibrated using in-situ monitoring data and used to predict the natural flow field. Figure 4 is a diagram showing the match between modeled (lines) and monitored heads (crosses); these boreholes are in a very good match thus the model and parameters are reliable for further simulation and design. The calibrated model then was used to simulate the PRB design for best remediation design. Initial design of the PRB for shallow and deep aquifers is shown in Figure

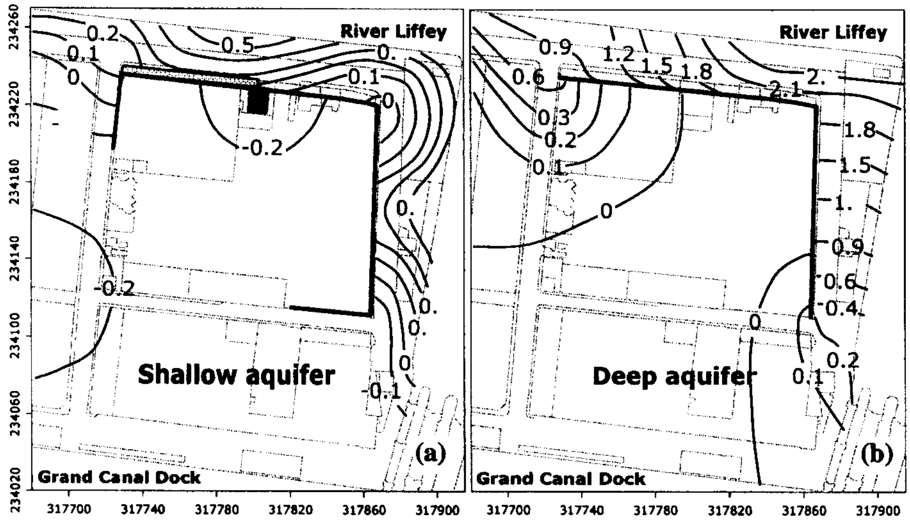
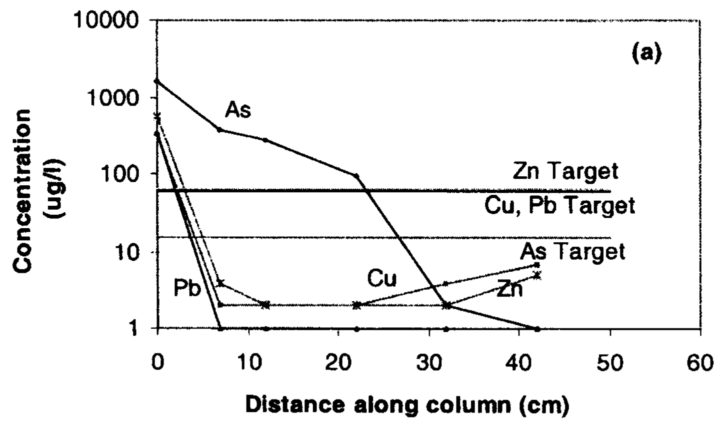


Figure 6. Snapshots of groundwater flow field of the two-aquifer system.

5. Based on these specifications of cut-off wall and reactor, groundwater flow fields of the two aquifers were calculated and shown in Figure 6. These are snapshots of the flow fields at high-tide moment, approximate 190 hours after the application of the PRB wall and reactor. The designed PRB captures the flow within the site satisfactorily with exception of: (a) the groundwater flow field in shallow aquifer (Figure 6a), is pretty flat and the cut-off walls at the bottom-right and top-left corner may be shorter to reduce the cost; (b) the flow field of the deep aquifer (Figure 6b), is not adequate at the top-left corner, which definitely needs to be improved.

Therefore, the model was run with various scenarios to obtain the best option for PRB design to reach a satisfactory flow field with a better cost-effective trade-off. The final scenario has the following specifications: the sizes of the slurry wall wings in the shallow aquifer are reduced to 10 m and 20 m for the top-left and bottom-right corners; a 60 m wing is added to the top-left corner in the deep aquifer; other conditions remain unchanged. The predicted flow fields are much improved, which are considered as the best option of the PRB design.

Finally, the feasibility study of the PRB reactor was followed in the laboratory to identify performance of the PRB to various contaminants (Gavaskar et al. 1998). This feasibility study was made in a 1-D Zero-Valent-Iron (ZVI) column for various metal contaminants. Figure 7 shows the treatability of ZVI on Copper and Arsenic under slow-flow condition (7a), and Copper, Arsenic, Zinc and Lead under fast flow condition (7b) respectively. The concentration of all these contaminants were reduced to below the required target levels within a short section in the ZVI column, which indicates successful treatability of the designed PRB.



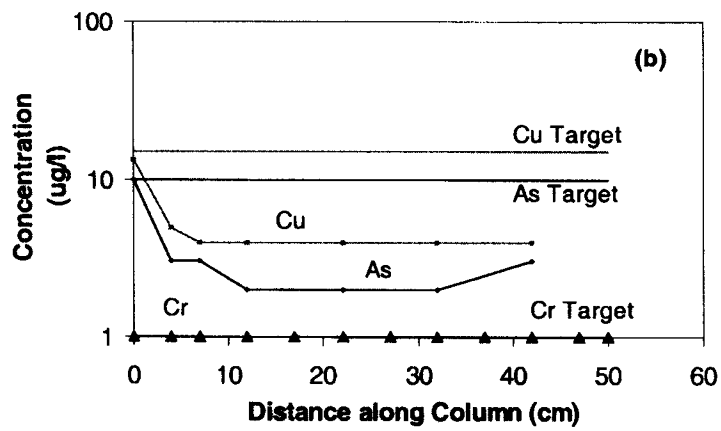


Figure 7. Feasibility study of the contaminants with ZVI: a) Cu and As; b) Cu, Zn, As & Pb.

It is demonstrated from this study that in-situ monitoring data, proper field tests and sound interpretation provide important support to successful modeling scenarios, which in turn produce high confidence in the understanding of flow field changes, contaminant pathways and environmental impacts. Numerical modeling is receiving a great deal of attention as a cost-effective method for the simulation and designing of in-situ groundwater cleanup strategies. It is particularly an efficient and powerful tool for site characterization, plan designing and performance prediction in risk-based contaminant remediation using PRB.

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