



Groundwater contamination transport through modeling approach: a case study in Kasur, Pakistan

Haroon Rashid^{a,*}, Jiro Takemura^b, Muhammad Aqeel Ashraf^c, Muhammad Faheem^c

^aFaculty of Engineering and Technology, Department of Civil Engineering, The Islamia University of Bahawalpur, Pakistan, Tel. +92-62-9255850; Fax: +92-62-9255537; email: rashid.haroon@iub.edu.pk (H. Rashid)

^bDepartment of Civil Engineering, Tokyo Institute of Technology, Tokyo, Japan

^cSchool of Environmental Studies, China University of Geosciences, Wuhan 430074, P.R. China

Received 21 May 2022; Accepted 2 August 2022

ABSTRACT

Assessment of contaminated sites having an anthropogenic source of contamination from industries is the need of the hour to properly investigate and search for mechanism of contamination, that is, how the pollution is spreading out and how much the life in those areas is at risk due to complex environmental scenarios existing at site. In this background Kasur tannery area was selected to explore the environmental situation regarding industrial pollution mainly caused by major pollutants being released from tanneries, that is, chromium. FEMWATER model was used to conduct contaminant transport simulations in the area. Three main scenarios were developed to simulate the site for contaminant flow. The first scenario was considered with adverse condition with a stagnant pond in the tannery area in operation with no treatment plant and drains in the area and this scenario was conserved for a duration of 20 y from 1980 to 2000, the second scenario was for no contaminant release into the environment due to properly collected wastewater systems and treatment plants. Furthermore, the third scenario was based on an existing situation, when the treatment plant was not working efficiently due to the release of excessive tannery effluent from the tannery units. The result of simulation showed very slow movement of contaminant plume indicating that stagnant pond in the tannery area has not affected the downstream side. After the year 2004, the generation of stagnant pond 2 due to heavy overflow also could not create any farther contaminant transport horizontally. Therefore, it has been suggested that, once the source of contamination has been stopped and controlled by focusing on the chemical treatment of the tannery effluent and the seepage prevention of the untreated effluent from the drains or leakages, the groundwater contamination might reduce by exhibiting natural attenuation.

Keywords: Tannery industry; Chromium; Groundwater modeling; Contaminant transport; FEMWATER; Pakistan

1. Introduction

Pakistan is blessed with extensive groundwater resource, which has been built due to direct recharge from natural precipitation, river flow and the continued seepage from the conveyance system of canals, distributaries, watercourses, and applications losses in the irrigated lands during the last 90 y. This groundwater source has a

potential of about 55 million acre feet (MAF), out of which about 48.69 MAF is being exploited by over 661, 853 private tube wells, and about 18,620 public tube wells for domestic, agricultural and industrial purposes. Province wise groundwater usage is 42.69 MAF in the Punjab, 3.5 MAF in Sindh, 2 MAF in Khyber Pukhtoonkhawa, and 0.5 MAF in Balochistan. The potential of groundwater exploitation in Azad Jammu Kashmir is only 16,800 AF while usage

* Corresponding author.

is above 4,300 AF. The Northern areas, the potential for groundwater exploitation is virtually none. Groundwater use is nearing the upper limit in most parts of Pakistan. In Balochistan the water table has been declining continuously. A number of studies have estimated that the deficit in Quetta sub-basin is about 21,000 AF per year and the aquifer storage will be exhausted in 20 y [1].

Pakistan has now essentially exhausted its available water resources and is on the verge of becoming a water deficit country. The per capita water availability has dropped from 5,600 to 1,000 m³ since the independence in 1947. The quality of groundwater and surface water, which are the main sources of water, is low and is further deteriorating because of unchecked disposal of untreated municipal and industrial wastewater and excessive use of fertilizers and insecticides [1].

It has been estimated that the total number of registered industries in Pakistan is 6634 out of which 1278 are considered highly toxic [2]. However, little attention has been given to the proper disposal of industrial waste. Recently, it has been realized that there is a significant threat of water-borne diseases, degradation of freshwater quality, environmental depletion and soil deterioration from the effluent and toxic emission of industries [3].

This research work was planned in district Kasur, Pakistan, which is famous for its Kasur Tanneries Industrial Area, operational for more than hundred years. With the usage of chromium in tanning industry, in early seventies, it started deteriorating the on-site environmental conditions and initiated soil and groundwater contamination. Chromium sulphate, the salt, was started as a chemical to help improving the finishing of leather [4]. Chrome tanning used chromium sulphate as a tanning agent. Tanning process stabilizes the collagen network of skin. After tanning, skins are called wet blue and are stored for sometimes and thereafter they are sorted out according to quality [5]. Not only, directly the soil but the groundwater also got severely affected by the continuous percolation of the hazardous chemical containing wastewater directly from the open fields and also from the unlined channels [6]. Industrial use of chromium has contaminated our environment and has created diverse health issues [7]. Considering the situation at research site, the tanneries discard 150 tonnes of wastes and 13,000 m³ of the effluents daily. Effluent amounting 2,500 m³ flows in Rohi Nallah and the remaining quantity is allowed to form three stagnant ponds covering an area of 132 ha. Chromium sulphate, lime, sulphides and animal tissues are the main pollutants. Daily discharge of poisonous chromium in the effluent is 300 kg [4]. Before year 2000 there was no treatment plant, and all the waste was disposed into the drain or left over in open fields. From the drain the wastewater was used for irrigation purposes as well. The effect of use of hazardous wastewater for irrigation is also questionable. Besides more than 400 acres area in the surroundings of the tanneries was completely soaked with tannery wastewater for decades, creating a very unaddressed environmental issue, preferably considered as a very significant matter regarding the health hazards and environmental impact on the whole area and the inhabitants [6]. The direct discharge of effluents from tanneries into water bodies has become a growing

environmental problem in these days. Most of these waste waters are extremely complex mixtures containing inorganic and organic compounds that make the tanning industry potentially a pollution-intensive sector [8].

Purpose of this research was to determine contaminated site assessment approaches in the study area. It includes, site characterization, understanding the contaminant mobility and retention to describe the behavior of the contaminant in different media and the effect of the contaminant on the health of the inhabitants. After characterizing the site in terms of contaminant availability and its behavior in soil and groundwater, it was required to simulate the chromium for its mobility in saturated and unsaturated zones. It was required to predict the movement of contaminant (Total chromium) in groundwater so that its potential impact on the quality of groundwater followed by its impact on human health could be evaluated. Furthermore, it was also aimed to work out the contaminant (total chromium) movement considering different possible scenarios based on the available facts and figures.

It was aimed to model the whole contamination scenario with the objective to understand subsurface hydrology regarding groundwater flow and solute transport mechanism in different soil layers. In this regard FEMWATER Model of GMS groundwater a modeling software package was used to conduct a coupled flow and transport in unsaturated and saturated zones in the study area. FEMWATER is a 3D finite element modeling software that is capable of modeling the groundwater flow condition in the aquifer [9]. The basic modeling approach constituted the development of different scenarios which most befitted the variety of possible situations which prevailed at the study site with the passage of time.

2. Methodology

2.1. Development of FEMWATER model

In this study, FEMWATER model was used for simulating the groundwater contamination due to total chromium subjected to leachate from the drains and stagnant ponds in the research area as described in the three scenarios presented in Fig. 1.

The three contamination scenarios were used to develop the model. The model was simulated for the duration of 31 y, representing the time frame from 1980 to 2011. It was assumed that stagnant pond originated in 1980 due to continuous discharge of initial 10 y from 1970 to 1980. It is also assumed that after 20 y presence the stagnant pond was dried in the year 2000 by constructing drains. Initially, the amount of 73 mg/L of chromium was used as a variable concentration for contaminant mass in the pond yearly for the predefined area. After 20 y the supply of discharge to the pond was stopped. For duration in between 2001 to 2004, 4 y were considered to be improved condition scenario as an ideal case in which no source of contamination existed at the site, due to proper working of the treatment plant at Kasur Tannery Industrial area and construction of drains for carrying the effluent to the treatment plant and for final disposal of treated water to main drain. Afterwards there was a third scenario in which

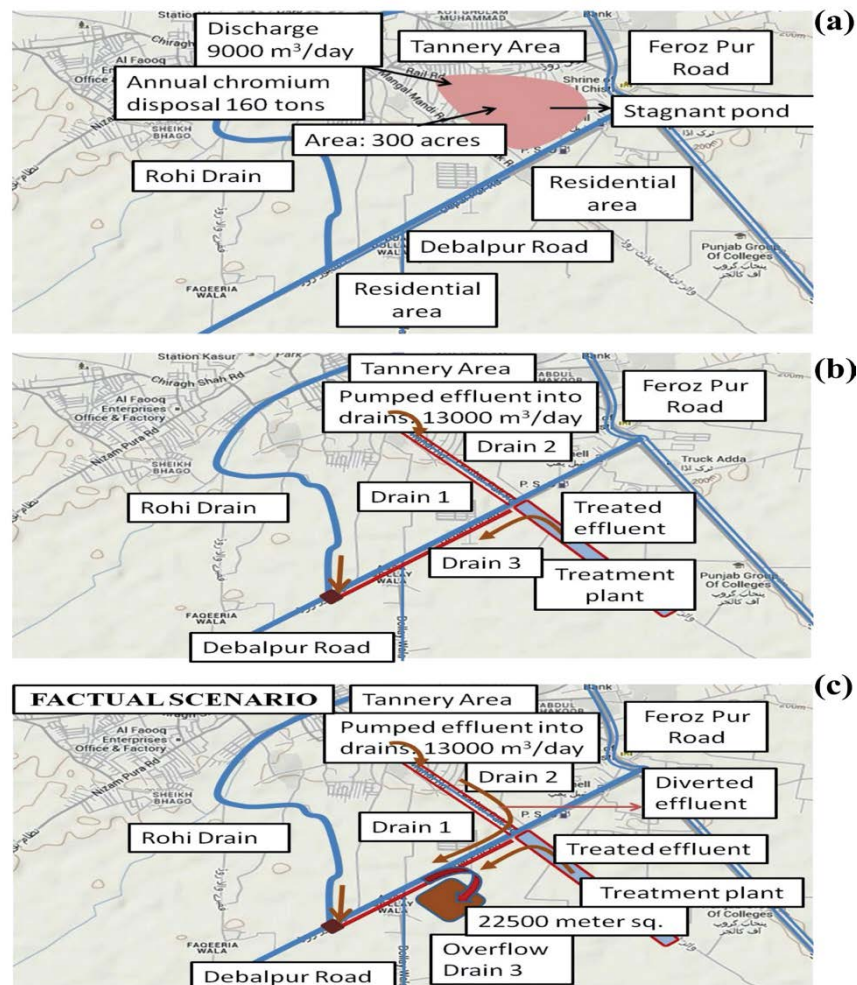


Fig. 1. Schematic diagram of adverse contamination scenario (a), improved condition ideal scenario (b), and factual scenario of contaminant transport (c).

the addition of contamination was used as input in the model due to overflowing of drain 3 in the form of a polygon, representing pond with same concentration influx as initially provided for the first stagnant pond as it was carrying untreated effluent. This condition was assumed to be continuous until the model time frame finished in the year 2011 after 7 y presence of the second source of contamination from the pond created due to overflow. Therefore, the supply of discharge was not stopped at the polygon mesh element boundary face until the model run time ended.

2.2. Validation of FEMWATER specifically concerning research site

To obtain specific research objectives based on the existing site conditions FEMWATER model was considered to be the most suitable tool to be applied for exploring the research site at Kasur thoroughly. FEMWATER is a 3D finite element, saturated/unsaturated, density-driven, flow and transport model. It's a Finite Element Model of

water flow through both saturated and unsaturated media. As the main source of contamination lies in the filtration of effluent from soil medium, therefore, FEMWATER was found more suitable to conduct simulation with particular reference to existing site conditions. The applied model was found to be the most suitable option regarding site characterization, groundwater modeling and contaminant transport to be conducted simultaneously. It has the ability to model saturated and unsaturated areas both. FEMWATER was selected based on available literature and its suitability for developing a model and its simulation. FEMWATER has been used to develop model domains and some of its features facilitate the utilization of soil texture characteristics to construct the model domain. This could be done using stratification, one of the significant features of FEMWATER. It was an important characteristic which was necessary to understand the sub soil characteristics and expanding them to larger areas. The most significant feature of FEMWATER which validate the application of this model for the research area is advanced 3-D soil analysis. This can be conducted by using stratification

which helps in generating complex soil profile domain of the area under investigation.

2.3. Formulation of FEMWATER

GMS includes a graphical interface to the groundwater model FEMWATER. It is a 3D finite element, saturated or unsaturated, density-driven, flow and transport model. It is designed to solve the following system of governing equations along with initial and boundary conditions, which describe flow and transport through saturated-unsaturated porous media [10].

2.4. FEMWATER model construction

FEMWATER is applied in the research area with the main objective to use the simulation for prediction of chromium contamination to move off-site and travel up to farther distances. This approach can be used to adopt best management practices in the affected area by taking preventive measures in terms of direct usage of soil and groundwater. It is particularly significant as most of the inhabitants are dependent upon the groundwater as one of the major sources of water. Water supply scheme from the municipality is still not available in the peripheries of the tannery area. Furthermore, contamination of soil is also one of the major parameters, which must be considered along with the groundwater contamination as the tannery area is surrounded by agricultural lands. People use the land as a major source of income and different crops and vegetables are cultivated in the agricultural lands just adjacent to the tannery area. It must also be considered that farmers in the vicinity use the tannery effluent directly for irrigation purposes without any treatment. Thus, it poses a direct health hazard due to its immense reliability on tannery effluent as wastewater. The modeling the outcome is to be used to define the boundary of the highly contaminated plume. It will restrict the seriously contaminated area and its radius of influence. Thus, boundaries can be predefined for future tube well (pump) installations so that contamination-free water can be drawn for the different uses including household usage, drinking water, and irrigation, etc. Studies of system dynamics have an application forward to understanding the complexities of existing contamination scenarios. The data obtained from the particle size distribution of soil samples collected at a fixed interval of 1.5 m up to the depth of 30 m during manual soil

boring helped in obtaining basic information about lithology of subsurface and ultimately in the description of layers formation. The groundwater characteristics and stratification obtained through the boring analysis are used to describe the vertical extent of the conceptual model. Overall 500 mm precipitation per year and 1500 mm evaporation were considered on an annual basis. The model domain was selected to represent the flow processes and contaminant transport pattern in the study boundary. The model domain included the hydrological features and the main sources of contamination within the area. The total length along east-west was 2,750 m while along north-south was 2,000 m. Using the borehole data obtained during site investigations, soil layer data and water table elevations were imported using model, to develop firstly solid data for the entire area up to the depth of 100 m and then generating a 3D mesh from using the same borehole defined horizons data. The vertical extent was based on soil bores conducted in the research area. Based on soil texture, the soil layers were divided into seven main classifications consisting of sand, sandy loam, loamy sand, loam, clay loam, silty clay loam, and silt loam. Based on these soil textures material properties were input into the model which is described in Table 1 [10].

The objective to use groundwater model was to interpret and characterize the site regarding the potential to contaminate the subsurface considering different contamination scenarios describing the realistic conditions of possible sources of contamination and their effect on soil and groundwater.

2.5. Hydrogeological characteristics and determination of input data for mass flux

Interaction between different hydrological units within the study area was studied in order to understand the total water flux and its movement in soil and aquifers.

2.5.1. Determination of initial and boundary conditions

Following boundary conditions were applied to the model. Significant hydrogeological features of the model domain are shown in Fig. 2.

2.5.1.1. Specified head boundary

This boundary condition was given to all the four sides of the model and drain 4 by providing head values on each

Table 1
Parameter values for different soil textures used in model

Materials	Saturated water content (ND)	Residual water content (ND)	Empirical constant alpha (1/cm)	Empirical constant (n)	Hydraulic conductivity (m/y)	Bulk density (kg/m ³)
Silt loam	0.45	0.067	0.02	1.41	39.4	1,380
Sand	0.43	0.045	0.145	2.68	2,601.7	1,690
Loam	0.43	0.078	0.036	1.56	91.1	1,430
Sandy loam	0.41	0.065	0.075	1.89	387.2	1,510
Silty clay loam	0.43	0.089	0.01	1.23	6.1	1,270
Clay loam	0.41	0.095	0.019	1.31	22.7	1,300
Loamy sand	0.41	0.057	0.124	2.28	1,277.5	1,630

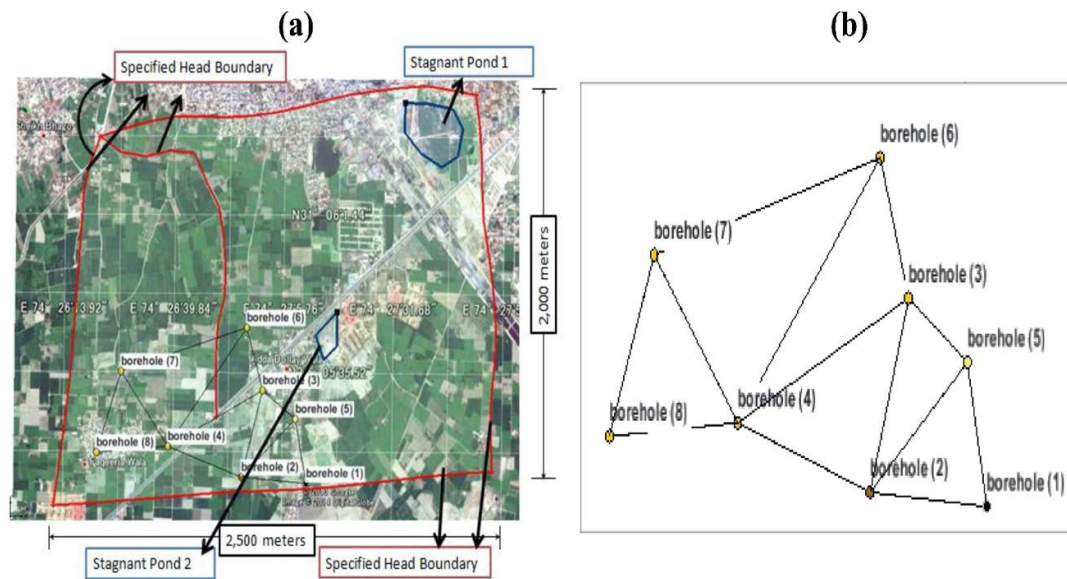


Fig. 2. Model domain presenting significant hydrogeological features and boundary conditions (a), and soil bore mapping for stratification (b).

end of the respective arc for the boundary. Most realistically the data obtained from field investigations and experimentation was used to describe the boundary conditions of the model domain. Arcs representing the boundary the domain of the model is described as a specific head with a maximum head of 2 m diagonally in a southwest direction. The major component of the model domain is “stagnant ponds” represented by a polygon. The total area covered by the polygon in the field is 400 acres or $1.62 \times 10^6 \text{ m}^2$ and it mainly constitutes tannery effluent released from the tanneries before the proper construction of a wastewater treatment plant and the effluent carrying drains. Previous studies indicated that about 74 kg of total chromium was being disposed of daily by the tannery units. The data utilized is obtained from the previous research work available in literature. Therefore, it was assumed that this stagnant pond remained a continuous source of subsurface contamination until the year 2000 when the drains were constructed to dry the stagnant pond and wastewater treatment plants were developed in the year 2003. Groundwater level, as measured in an observation well, reflects the amount of water in storage in the monitored aquifer. When recharge exceeds natural discharge plus abstraction, groundwater levels rise. When recharge into the soil is less than natural discharge plus abstraction, groundwater levels fall.

Comparison of measured groundwater levels with long term averages provide an indication of the state of groundwater resources within an aquifer. Observation over several years allows the prediction of aquifer response to current climatic and hydrological conditions. First of all, the water table readings were measured in feet and then converted to meters to maintain a general format.

2.5.1.2. Flux boundary

To incorporate flux, due to evapotranspiration and discharge flow rate, flux boundary conditions were applied at

the surface of the model. For variable concentration as used for contaminant transport phenomenon, transient concentration was applied at the element faces for accommodating the stepwise provision of contaminant mass, for both the polygons representing stagnant ponds.

Soil bores conducted in the research area are shown in Fig. 2, describing the wide distribution and location of the bores for soil and water analysis. Soil texture and the stratification of the subsurface is shown in Fig. 3. Mostly the soil texture observed is of loamy or sandy. However, the top elevation being generally flat, a similar trend is water table elevations can be observed. First water table level on average exists at 10.7 m while the second water table level on average lies at 27.4 m.

3. Results and discussion

3.1. Model simulation for three scenarios

It was attempted to obtain the most realistic outcome of the model simulation so as to determine the pattern of contaminant transport in the study area minimizing the irregularities in the contamination behavior along with reducing the chances of exaggerated assumptions based on the facts that no literary evidence of the level of contamination could be obtained.

The most important factor is the precise description of the soil strata and its characteristics to obtain a more realistic model simulation. In this regard, Fig. 3 shows the geographic position of the soil bores based on which lithology of the subsurface was defined. The differentiation is based on the upstream side of the drains and the downstream side. In both cases, it can be observed from Fig. 3 that the dominating soil texture is exhibited in terms of sand layers while other soil characteristics are not that much in the extent to be significant enough to have any impact on the behavior of the contaminant with the soil

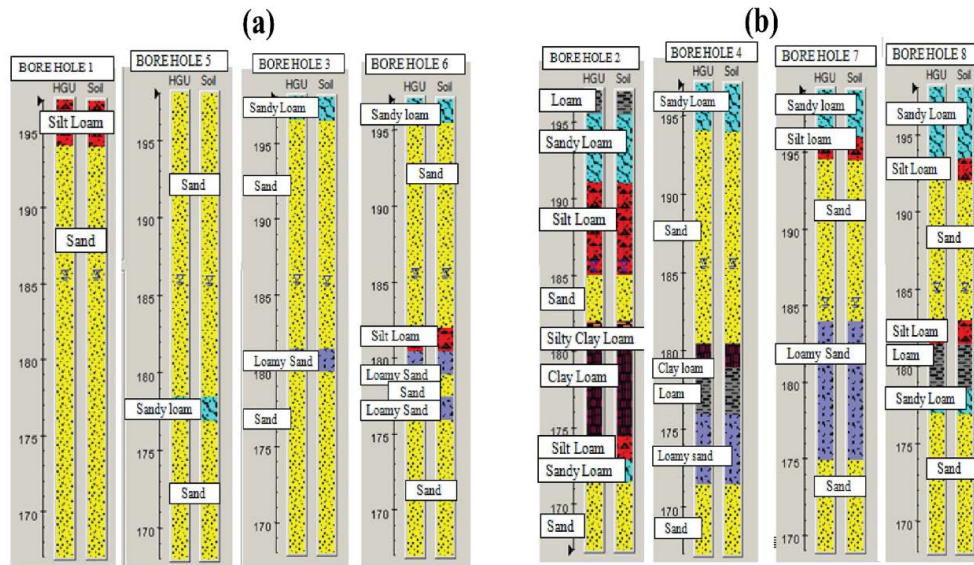


Fig. 3. Geological profiles of studied area on upstream (a) and downstream (b) side of drains.

strata. However, remarkable characteristics variations could be observed on the downstream side in all the soil bores that are bore hole 2, 4, 7 and 8. This could be one of the confirmations of the retention of the contaminant in the deeper layers, particularly in soil bore 8.

Using stratification technique application in the model FEMWATER, subsurface strata were expressed based on the boring log data. However, the depth of the domain was fixed up to 30.5 m (100 ft). Due to the unavailability of the boring locations at a wider range and difficulty in moving the mechanical bore machinery to remote areas along with power supply issues, soil bores on an extensive level could be conducted. However, these soil bores were supported by further additional 6 soil bores at the extended boundaries of the study area so to validate the soil stratification behavior as described in the domain of the model. These extended soil bores were conducted to calibrate the groundwater flow direction as well.

Fig. 4 describes the ortho projections of soil bore log data as obtained from the field and investigated for the soil texture analysis in the laboratory. Stratigraphic framework of the 3 dimensional cross-section can be observed in the demonstration.

3.1.1. Steady-state simulations and calibrations

The data files were prepared pertaining to the required information regarding the mass flux and infiltration. Furthermore based on the information related to the hydraulic head in the study area, as obtained from the observation wells (monitoring wells) was simulated for the given boundary of the conceived model for 1 y. Discrepancies were observed in the smooth flow pattern of groundwater due to unsymmetrical directions of nodal velocity vectors. It was mainly subjected to uncertainty in the data related to the mass influx and infiltration rates. There was no previous data available on the hydraulic head in the study area to cross-check the consistency in the data related to head

values in the observations wells. Rate of infiltration into the soil layers was also very inconsistent regarding smooth and continuous recharge in the soil medium and the groundwater aquifer. Mass flux which was used to define the initial conditions of the contaminant concentrations being entering into the model domain was also unreliable due to non-availability of the previous information about the discharge of effluent and constantly changing contamination transport scenarios. There was an intermittent discharge of effluents from the tannery units therefore to ensure the uniformity of the contamination behavior was not feasible. Observation heads obtained in the year 2009 was the only source of determination of hydraulic head to work out the groundwater flow directions, which were counter checked next year in 2010 and were found to be the same as before. Thus, the hydraulic head was observed to be almost horizontal. In Table 2 the difference in the water table for 2 y can be observed. To overcome the uncertainty in the data, head values were fixed on trial and error basis to maintain the steady flow conditions.

Fig. 5 describes the year wise model simulations for the total chromium transport based on the predefined soil and hydrological conditions. As the simulation was governed by three different contamination scenarios, therefore, the behavior of the contaminant transport was also very much divergent, particularly numerous uncertainties also were a major factor while demonstrating the impact of contaminants on the study area. The main source of contamination in the study area was found to be present in the form of clusters rather than showing a specific source of contamination may be in the form of spillage. Neither the source could be clearly described and measured for its impact on soil and groundwater contamination. There was an intermittent supply of contaminants to the study area being influenced by so many external factors. Inappropriate data and its authenticity were always a big question mark in obtaining the rational outcome of the model simulation which was run for the whole duration while the contamination was

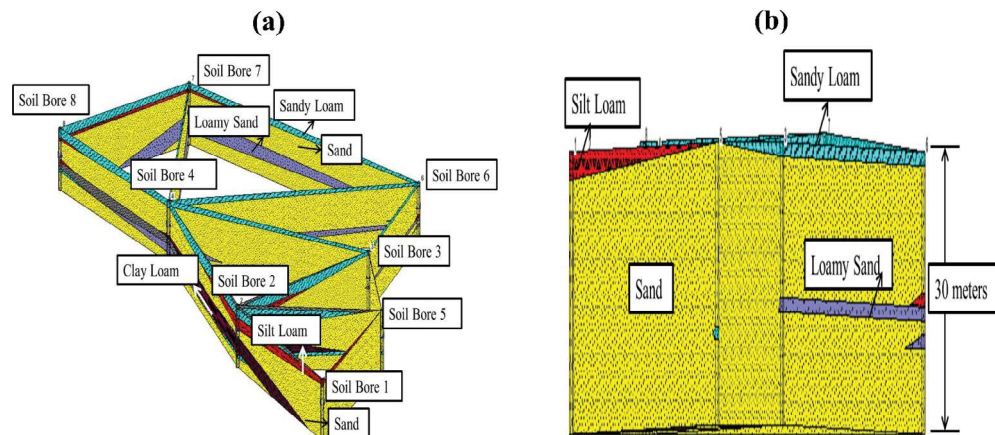


Fig. 4. Lithology of the soil bores (ortho projections) showing overall trend of the soil texture showing dominating sand layers with thin bands of loam and silt clay (a) and lithology of the soil bores (side view) dominating the sand layers (b).

being fluxed into the soil and groundwater considering different scenarios which prevailed during this time duration. The main source was considered to be the stagnant ponds which were used for disposing of the tannery effluent since 1970. It can be observed in Fig. 5 for the simulation of year 1 that gradually the concentration is increasing and after the time interval of 10 y the contaminant from the contaminant source has sufficiently spread out in the nearby vicinities. This was the time when the residents started having the adverse effect of these contaminants and groundwater contamination as it was the only source of water available at that time in the 1980s. The flow of contaminants is under the influence of so many factors mainly affected by the soil characteristics and hydrogeological formations. However the previously run model for calibration purpose and defining a symmetric groundwater flow conditions only has shown the same trend of contaminant as governed by the groundwater movement. It can be observed in Fig. 6, where nodal velocities of the groundwater flow are in accordance with the contaminant transport model simulation as shown in Fig. 5. As described earlier that there was a huge variation in the observations for different scenarios, thus the simulations are also exhibiting the same variation trends in terms of contaminant transport for the desired time duration for regular time intervals. The model simulations for year 31 can be observed as a combination of all the different scenarios which are varying from time to time.

The total period of 31 y with 1-y time step was simulated for all the three contamination scenarios simultaneously as explained earlier in one simulation to observe the combined effect of overall contamination conditions at the site. The demonstration of the model simulation as given in Fig. 5 is more accurately described in Figs. 6 and 7. The nodal simulations for all the different scenarios can be very understood from these figures which are showing the contaminant movement following the pattern of groundwater flow directions as shown in Fig. 6a.

Considering multi factors which are affecting the contaminant coupled movement of groundwater, the subsurface groundwater aquifers become highly significant no matter how much concentration of chromium is present in soil and

groundwater. This argument is further augmented by the typical nature of the soil strata which is varying so abruptly within the study area. Huge variation in the soil content and its behavior towards the contaminants from tannery effluent exists as major uncertainty to accurately define the contaminant transport mechanism in the study area. The soil formation varied from fine to coarse particles therefore developing not completely impermeable rather slightly permeable.

3.2. Results of simulation

The model run for the time duration of 31 y showed the output in the form of nodal velocities and concentration contours for every unit time step. From nodal velocity vectors presentation of the groundwater flows direction obtained as shown in Fig. 6a. Following the groundwater direction normal contaminant flow trend can anticipate. In Fig. 6b the flow pattern of contaminant for year 1 time step can be observed. The first scenario is presented only for stagnant pond 1, therefore the results show the slight movement of the contaminant plume following the groundwater flow directions as guided by nodal velocity vectors. Fig. 7a shows the contaminant plume for a time step of 20 y. It was observed that plume shifted only up to 1,150 m in x-axis while along the y-axis the plume moved up to 1,365 m distance. After 20 y time period no further discharge was assumed to enter the stagnant pond 1 but still there is an obvious movement of plume following the direction of groundwater both along the x-axis and y-axis as clear from Fig. 7b. Stagnant pond 2 started discharge into the soil after the time step of year 25, therefore the combined effect of both ponds can be observed in Fig. 7b.

It can be observed that the overall groundwater movement is very slow. Table 2 indicates that there was no groundwater movement observed during the monitoring period of 1 y from December 2009 to December 2010. This flat groundwater level was subjected to low precipitation on average 500 mm/y and complex geological formation. The combined plume of both the ponds just traveled the distance of 1,385 m along the x-axis and 2,000 m along the y-axis and hardly reached monitoring wells location with

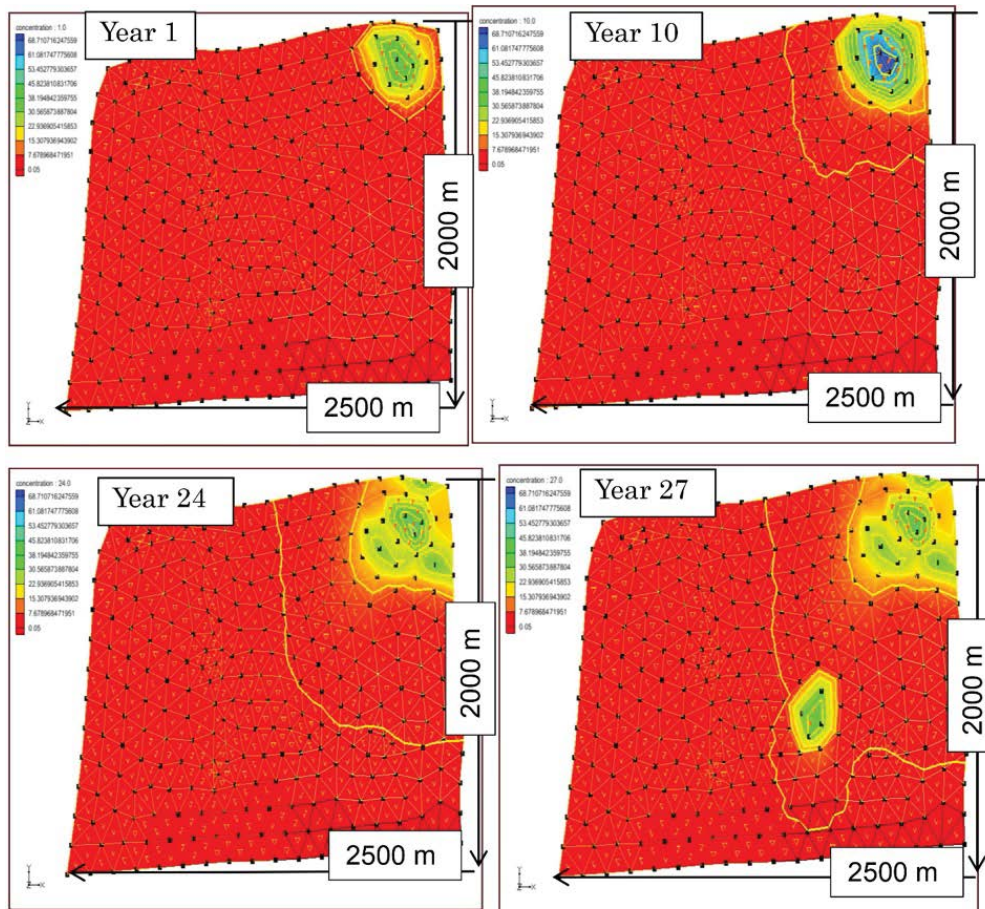


Fig. 5. Concentration variations at different time intervals and its movement graphics.

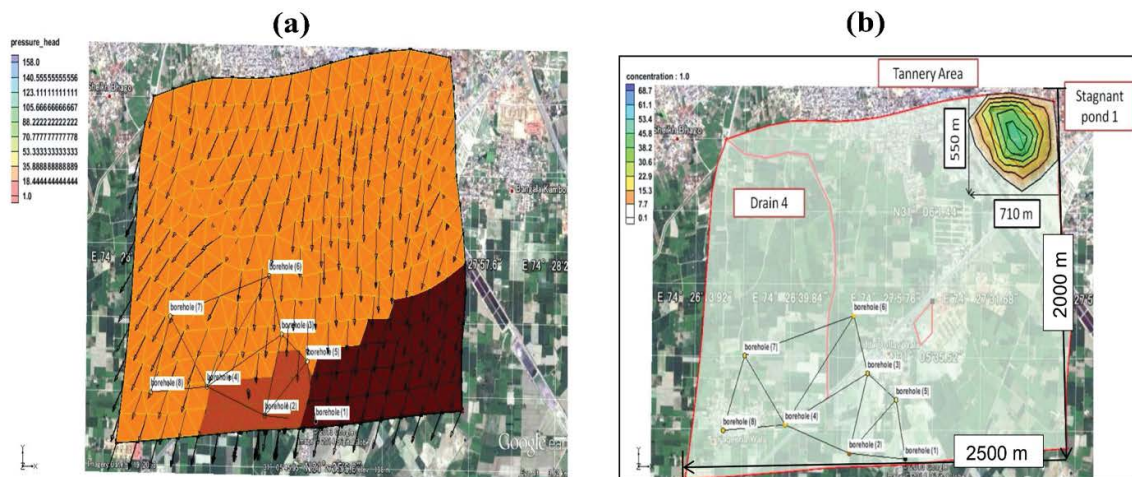


Fig. 6. Nodal velocity vectors showing groundwater flow directions (a), Concentration contours for stagnant pond 1 after time step of 1-y (b).

minimum concentration of 0.1 mg/L (Fig. 7b). Therefore, it can be assumed that presently the stagnant ponds are not causing any serious threat to downstream areas. However the high movement of concentrations to deeper depths are

evident from Fig. 8a showing the front view of the model the indicated concentration of up to 22.7 mg/L reaching 100-m depth for stagnant pond 1, while for stagnant pond 2 this much concentration level is at 20 m depth from the surface

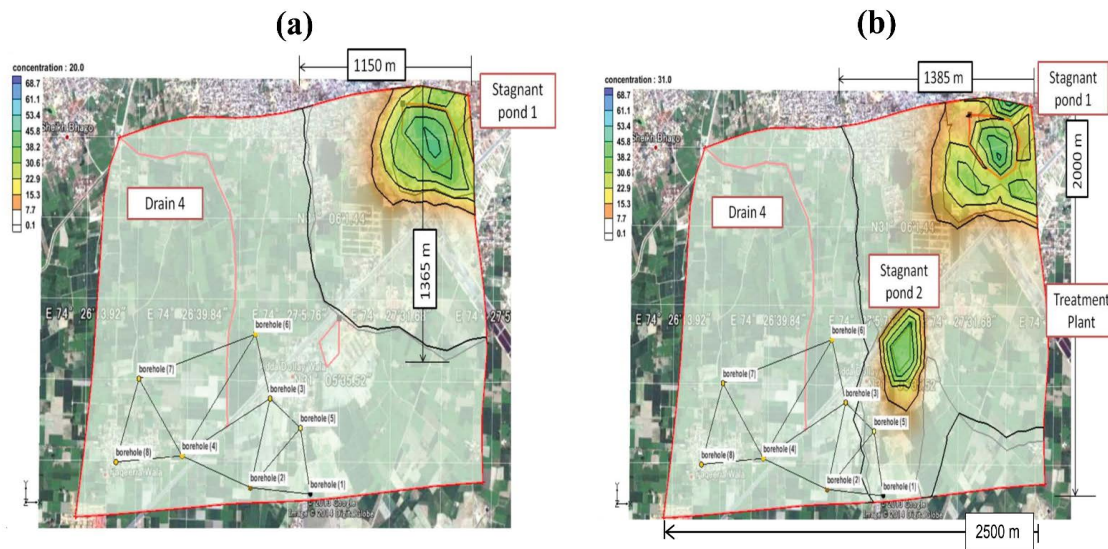


Fig. 7. Concentration contours for stagnant pond 1 after time step of 20 y (a), for stagnant ponds 1 and 2 after 31 y (b).

Table 2
Water table levels and its yearly-based comparison

Bore hole	Elevation from sea level	Water table level 2009		Water table 2010	
		First WT	Second WT	First WT	Second WT
BH 1	197 m	185.7 m	169.6 m	185.7 m	169.6 m
BH 2	197 m	185.7 m	169.6 m	185.7 m	169.6 m
BH 3	198 m	186.1 m	170.6 m	186.1 m	170.6 m
BH 4	197 m	185.7 m	169.6 m	185.7 m	169.6 m
BH 5	198 m	186.1 m	170.6 m	186.1 m	170.6 m
BH 6	197 m	185.7 m	169.6 m	185.7 m	169.6 m
BH 7	199 m	185.3 m	171.6 m	185.3 m	171.6 m
BH 8	198 m	185.2 m	169.6 m	185.2 m	169.6 m

beneath the stagnant pond. Also, both cross-section and side view pictorial projections of model simulations at significant time intervals were presented in Fig. 8b and c.

3.3. Overall summary of findings

Overall, the existing situation regarding soil contamination, groundwater contamination and wastewater condition was described in such a way to present the realistic site characterization approach in the research area. The purpose was to build a firm foundation regarding the level of contamination as well the different sources of contamination so that the contaminated site of Kasur Tannery area may be thoroughly assessed. As there was a lack of authentic background information about the site, these sites conditions provided a reliable source of information to lead towards model development procedures.

FEMWATER module was selected to evaluate contaminant transport modeling in the study area. In this regard the main contaminant considered was total chromium. The data previously obtained from the site investigations were used

as input data for the model running and simulations. Basic physical and chemical properties of the soil and other parameters which were necessary for the development of realistic conditions in the the model was conducted and analyzed. This data was used to describe a realistic soil profile existing beneath the ground surface. Based on these readings model domain was defined and initial and boundary conditions were allocated to this domain. Three different model scenarios were considered for running the model. These three scenarios were Adverse, ideal and factual condition-based scenarios which were used to describe the overall changing conditions at the site during different periods, where maximum time simulation was decided to be 31 y starting from 1980 to 2011. These changing scenarios showed the variations in the input levels of contamination in the form of influx into the subsurface and changing conditions of different sources of contamination as well at the site during the assumed period of model simulations. Main features of the model development include the conditions like a stagnant pond adjacent to the tannery area as the main source of contamination for the first 20 y of the model simulation.

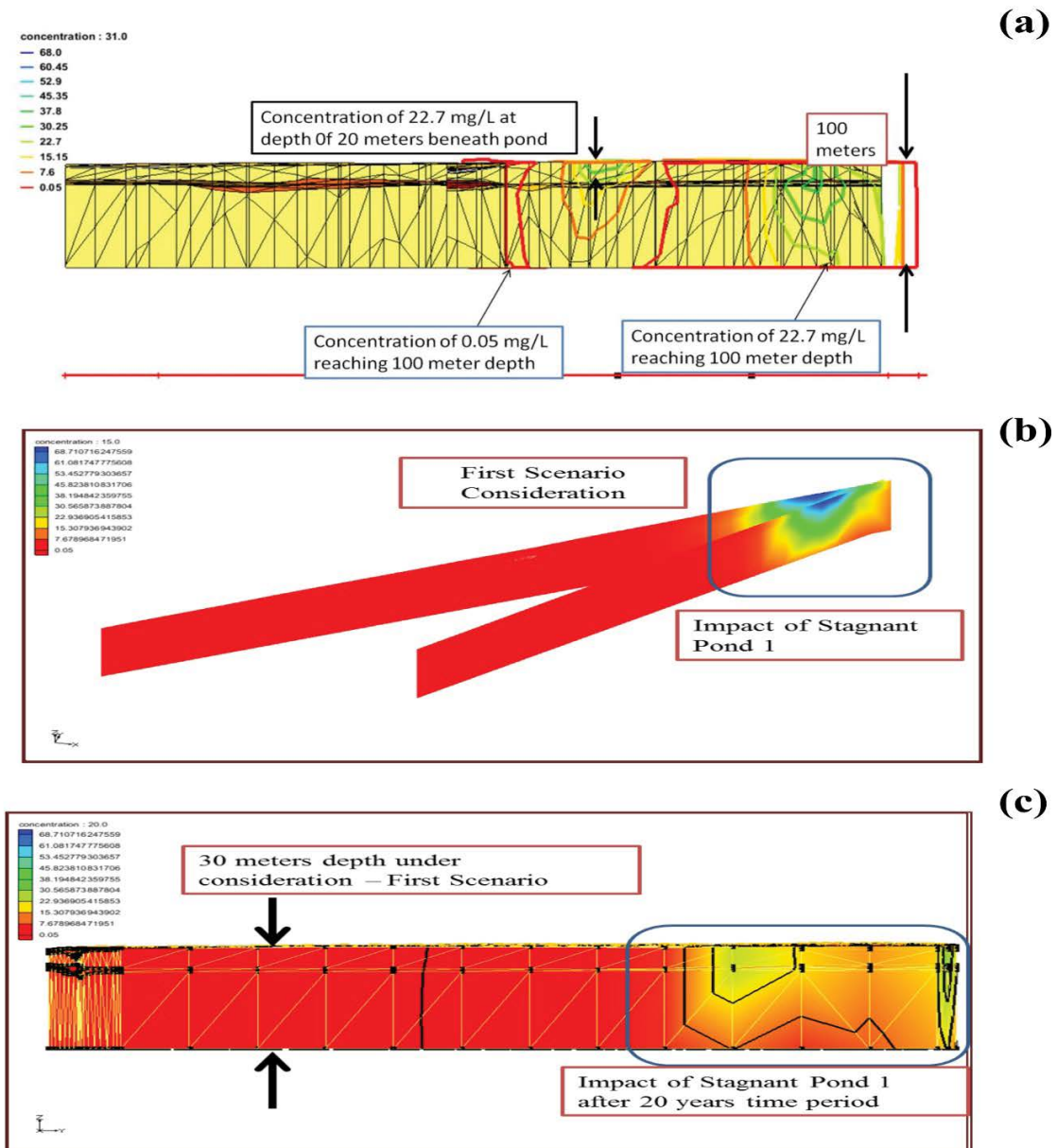


Fig. 8. Concentration contours for stagnant ponds 1 and 2 from side view of model (a), different pictorial projections of model simulations at significant time intervals, cross section along section AA'' and BB'' at the time interval of 15 y (b), Side view of the model simulation at the time interval of 20 y (c).

Later the drains were constructed to carry the wastewater for final disposal to the treatment plant. Furthermore, the extensive flow of the effluent worsens the existing situation and described the inefficiency of the treatment plant and the inadequacy of the wastewater management approaches at the site. Another important feature is the flat subsurface soil profile showing minimum availability of head to facilitate the movement of groundwater in the aquifer, which left an intense impact on the movement of contaminant as justified with the model simulations.

Subsurface soil profile and nature of the soil exhibits very tough conditions for the movement of the contaminant into

the soil or along with groundwater aquifer. Simulations for 31 y duration depict the very slow movement of contaminant, that is, only 1.38 km along x-axis and 2.0 km on the y-axis direction. Therefore, most of the contamination is basically due to localized interference of source of contamination with the groundwater aquifer or loose subsurface soil strata as described in the previous chapter. Evapotranspiration is also one of the major factors which facilitated the drying and evaporation of the contaminant due to extremely adverse hot weather in the study area during the summer season.

The simulation of total chromium for 31 y, based on different scenarios finally concluded complex subsurface

conditions leading to slow movement contaminant on lateral and vertical directions. The major focus of simulation studies was to forecast the extent of spreading of the contaminant in the surrounding areas of the city and the tannery units. It was found that considering the three possible scenarios as explained, total chromium has not been transported to longer distances than 1.38 km in the east-west direction, that is, lateral movement, while the maximum limit for contaminant transport is 2.0 km on north-south side, that is, vertical direction along the drains for a simulation period of 31 y. In this regard, the results of groundwater analysis as monitored periodically reasonably explain the present conditions of contamination. Considering the average values and ranges of groundwater sample, the total chromium concentration is gradually describing a reducing pattern as justified by the simulation results shown in Fig. 6a.

4. Conclusions and recommendations

To address the increasing demands of the city, it is recommended to develop a new sewerage system for the city and instead of disposing the municipal wastewater into Drain Rohi, it should be carried through main sewers for final disposal. Drain Rohi should be only used for carrying fresh water for irrigation purposes along with carrying excessive storm water during the rainy season. Once carrying fresh water, Drain Rohi can play a vital role in the natural attenuation of the contaminated soil in the entire research area along with the Debal Pur road by seepage through the sidewalls and bottom of the drain. It is highly recommended that open fields adjacent to the tannery area and along the drains, which are heavily soaked in tannery effluent, once eliminated and dried, should no more be used for any

human activity, especially for residential purposes. Rather these open fields and landmarks should be conserved and safeguarded by proper vegetation sheeting and fencing.

References

- [1] M.A. Kahlown, M.A. Tahir, H. Rasheed, *Water Quality Status, Third Report 2003–2004*, Pakistan Council of Research in Water Resources Islamabad, 2005.
- [2] S. Mubin, S. Gul, M.I.A. Khokhar, M. Ashraf, Statistical solution for the industrial waste problem, *J. Drain. Water Manage.*, 6 (2002) 55–68.
- [3] E.M.A. Qureshi, A.U. Khan, S. Vehra, An investigation into the prevalence of water borne diseases in relation to microbial estimation of potable water in the community residing near River Ravi, Lahore, Pakistan, *Afr. J. Environ. Sci. Technol.*, 5 (2011) 595–607.
- [4] M. Hussain, *Environmental Degradation – Realities and Remedies Ferozsons (Pvt.) Ltd.*, 2000.
- [5] S.W.S.B. Dasanayaka, G.D. Sardana, Technology issues in Pakistan's Leather Tanning SMEs, *J. Manage. Bus. Econ.*, 4 (2009) 167–179.
- [6] M.A. Rehman, Evaluation of technical and social aspects of environmental infrastructure projects – a case of Kasur Tanneries Pollution Control Project (KTPCP), Pakistan, *J. Archit. Plann. AIJ*, 578 (2004) 99–107.
- [7] S. Andleeb, A comprehensive review on chromium: toxicities and detoxification, *Punjab Univ. J. Zool.*, 29 (2014) 41–62.
- [8] J.C. Akan, E.A. Moses, V.O. Ogugbuaja, J. Abah, Assessment of tannery industrial effluents from Kano Metropolis, Kano State, Nigeria, *J. Appl. Sci.*, 7 (2007) 2788–2793.
- [9] M.S.L. Insigne, G.-S. Kim, Saltwater intrusion modeling in the aquifer bounded by Manila Bay and Parañaque River, Philippines, *Environ. Eng. Res.*, 15 (2010) 117–121.
- [10] H.C.J. Lin, D.R. Richards, C.A. Talbot, G.T. Yeh, J.R. Cheng, H.P. Cheng, N.L. Jones, FEMWATER: A Three-Dimensional Finite Element Computer Model for Simulating density – Dependent Flow and Transport in Variably Saturated Media, Technical Report, CHL – 97–12, 1997.