Numerical modeling of the environment impact of landfill leachate leakage on groundwater quality-A field application

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Abstract—**There are more than 372 big uncontrolled landfill areas in China. Waste disposal facilities are mainly responsible for the gradual quality degradation of groundwater. This paper reports an integrated study undertaken to develop an environmental assessment of the uncontrolled sanitary landfill area of the city of Jiaxing, Zhejiang, China. The USGS modular 3D finite difference groundwater flow model (Mod- flow) and Modular 3D Finite Difference Mass Transport Model (MT3D) software were used to simulate groundwater flow and contaminant transport modeling. The results indicated that landfill leachate leakage has significant effect on groundwater quality**.

Keywords-environmental impact ; groundwater ; landfill leachate

I. INTRODUCTION

One of the most common waste disposal methods for solid wastes is by landfilling below or on the land surface. All over the world, about 70% of waste disposal is by landfilling, especially in the underdeveloped and developing countries. The dumping of solid waste in uncontrolled landfills can cause significant impacts on the environment and human health. Some incidences have been reported in the past, where leachate had contaminated the surrounding soil and polluted underlying ground water aquifer or nearby surface water [1][2]. Generally, the landfill leachate pollutes the water resource by three ways: 1. the downward transfer of leachate contaminates groundwater; 2. the outward flow causes leachate springs at the periphery of the landfill that may affect surface water bodies; 3. polluted groundwater seep to surface water (Fig.1). The principal concern is the pollution potential of the migration of leachate generated from the landfill site into groundwater. In the past 10 years, some models have been established for modeling leachate transport in groundwater [3] [4] [5] [6]. In most studies, Chloride is often used as a simulation element to confirm contaminant plume. And, surface water quality is in turn affected by the seepage of leachate polluted groundwater. Hence, leachate seepage is a long-term phenomenon that must be prevented in order to protect natural water resources.

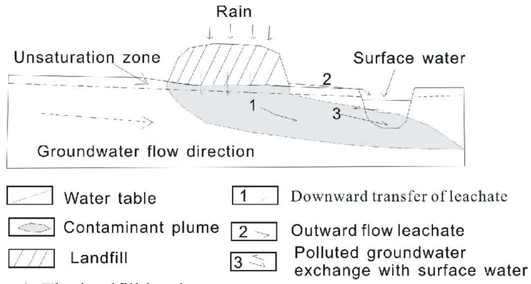

Figure 1. The landfill leachate transport system

In this paper, the potential contamination risk due to leachate leakage to the aquifer beneath a municipal solid waste landfill is examined. The Municipal Landfill of the City of Jiaxing (JXL) in China was selected for field application as a potential contamination of the aquifer beneath the landfill, may have a significant impact on public health and the local economy. The main objectives of this paper are the characterization of the leachate produced at the JXL and the hydrogeological characterization of the area of study, which includes the underlying aquifer. A groundwater flow and leachate mass transport model of the hydrogeological region beneath the municipal landfill was developed in order to examine the impact of leachate seepage from the JXL into groundwater.

II. LEACHATE CHARACTERISTICS

Leachate is the main medium for the transport of contaminants from the landfill to groundwater and surface water. Landfill leachate is formed from the infiltration and passage of water through solid waste which results in a combination of physical, chemical and microbial processes that transfers pollutants from waste materials to the water [7][8]. Leachate from municipal landfills contains a complex variety of organic and inorganic compounds. Many factors influence the leachate composition including composition of solid wastes, moisture content, the degree of compaction , hydrology of the site, pH of water , climate, age of the fill and other site-specific conditions including landfill design and type of liners used, if any [9][10].

Under normal conditions, leachate is found at the bottom of the landfill and moves through the underlying strata. Although, some lateral movement may also occur, depending on the characteristics of the surrounding

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material, leachate percolates through the underlying strata and many of its chemical and biological constituents will be removed by filtering and absorptive action of the material composing the strata. In general, the extent of this action depends on the characteristics of the soil. The exact volume of the produced leachate cannot be easily estimated as it depends on groundwater infiltration and waste composition.

The hydrometeorological conditions in the area of the JXL and its surroundings are of high importance as they affect the hydrogeological status of the area, leachate production and subsequently the risk of contamination. The rainfall in the area of the landfill is relatively high (1600–2000 millmeter/year), and, as a result, large quantities of water reach the area of the landfill as rainfall and surface run-off. The seasonal distribution of rainfall and surface run-off is uneven over the year: 60% of rainfall occurs during summer. Due to the uneven distribution of rainfall, leach production is extremely high during summer and practically occurs during the months of June, July and August. Air temperature in combination with moisture also affects leachate production within the landfill. With 10 years of operation, the leachate production of the JAX was 200–350 meter3/day and the observed values of leachate composition for the JXL are listed in Table 1.

III. OUTLINE OF STUDY AREA

A. *Characterization of the landfill*

JXL is located 1.5km east of the City of Jiaxing in the area of Renzhong village (Fig. 2). The landfill is used for the disposal of the municipal solid waste of the City of Jiaxing since 1996 and was active till September, 2007. The JXL is a landfill area of about 45000m^2 with an average of 250-450tons/day disposed (Table 2). Municipal solid wastes include all wastes

Table 1. Leachate composition at JXL

Constituent	MLP (2006) Mean values (mg/l)
COD	306
K^+	1039
Na^+	735
Cl^-	1290
Mg^{2+}	29.2
Fe	1.66
NH^{4+}	700
CO_3^{2-}	80.6
SO_4^{2-}	207
NO_3^-	451
TDS	7364

Table 2. Annual waste disposedin JXL

Year	Waste (tons)
1998	51000
1999	53000
2000	60000
2001	65000
2002	71000
2003	72000
2004	80000
2005	90000
2006	85000

under the control of local authorities or agents acting on their behalf, such as household wastes, street litter, municipal parks, garden wastes and some commercial wastes from shops and smaller trading estates, where local authority waste collection agreements are in place. Based on investigation, the main characteristic of the municipal solid waste is the high percentage of organic matter (29%) that leads to increased production of leachate.

Figure 2. Area of study

B. Characterization of study area

The study area is located in the Yangtze Delta with high rainfall and dense surface water cover, marked by high rate of groundwater and surface water exchange (Fig. 3). JXL is in the vicinity of surface water bodies and the surface water flow velocity is very slow (<300meter/day). The altitude of the landfill area is between 2-4m above mean sea level. The JXL is around and includes the villages of Renzhong and Hexi. The closest inhabited area to the landfill is the village of Renzhong, 200m upstream. The Pinghu Lake traverses the landfill site from west to east. A conceptual geological plan of the study area is shown in Fig. 4. The main geological formations observed in the area of study are summarized as follows:

(1) Alluvial deposits of hydrogeological importance exist all through the study area with thickness of 5-10m.

(2) Distinct interbed sand (aquifer) in the midst of two aquitard (clay layer) (Fig.5).

(3) Hydraulic conductivity of unconfined aquifer varies (k =0.5~3meter/day), the grain size distribution gradually decreases from east to west, and that of the confined aquifer is uniform (k=3meter/day).

(4) There are two clay sediment layers. The grain size distribution is very uniform, and the permeability of the formation is significantly low (k= 0.01 meter/day).

The basic hydrogeologic characterization of the area of study is summarized in Table 3.


Figure 3. Landfill area for redevelopment into a park (September, 2007)

IV. MATHEMATICAL MODEL

A. Groundwater flow model

The three-dimensional (3D) movement of groundwater of constant density through porous earth can be described by the partial differential equation:

$$\frac{\partial}{\partial x}(k_x \frac{\partial x}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial y}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial z}{\partial z}) + w = \mu_s \frac{\partial h}{\partial t} \quad (1)$$

$$h(x, y, z, 0) = h_0(x, y, z)$$

$$h|_{B1} = f(x, y, z, t)|_{B1}$$

$$k\frac{\partial h(x, y, z, t)}{\partial n}|_{B2} = q(x, y, z, t)|_{B2}$$

where k_x, k_y, k_z are hydraulic conductivity along the x, y, and z -axis (LT^{-1}); h is the hydraulic head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); μ_s is the specific storage (L^{-1}); and t is time (T); h_0 is initial hydraulic head (L); $f(x, y, z, t)|_{B1}$ is the first boundary; $q(x, y, z, t)|_{B2}$ is the second boundary. Equation(1) describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions. Analytical solutions of (1) are rarely possible except for very simple systems; therefore numerical methods must be employed to obtain approximate solutions as is the use of the popular finite-difference method based on discretization of points in time and space.

B. Groundwater contaminant transport model

Simulation of ground-water flow is performed by the numerical solution of both ground-water flow and solute-transport equations. The partial differential equation describing the 3D transport of dissolved solutes in the groundwater can be written as follows:

$$\frac{\partial(\theta C^k)}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij} \frac{\partial C^k}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta v_i C^k) + q_s C_s^k + \sum R_n \quad (2)$$

Where θ is porosity of the subsurface medium, dimensionless; C^k is the concentration of contaminants dissolved in groundwater of species k, (ML^{-3}); t is time, (T); $x_{i,\ j}$ is distance along the respective Cartesian coordinate axis,(L); Dij is hydrodynamic dispersion coefficient tensor, (L^2T^{-1}); v_i is seepage or linear pore water velocity, (LT^{-1}); it is related to the specific discharge or Darcy flux through the relationship, $v_i = q_i / \theta$; q_s is volumetric flow rate per unit volume of aquifer representing fluid sources (positive) and sinks (negative), (T^{-1}); C_s^k is concentration of the source or sink flux for species k, (ML^{-3}); $\sum Rn$ is chemical reaction term, ($ML^{-3}T^{-1}$).

In this model, the MT3D, a modular three-dimensional finite-difference groundwater solute transport model based on dispersion approach, coded by [11] was applied to solve the solute-transport equation. The model is based on the assumption that changes in the concentration field do not significantly affect the flow field. This allows the user to construct, calibrate and validate a flow model independently. The calculated hydraulic heads and various flow terms from the current USGS modular 3D finite difference groundwater flow model (MODFLOW) solution are used to set the basis for simulating and predicting the solute transport behaviors of the groundwater system.

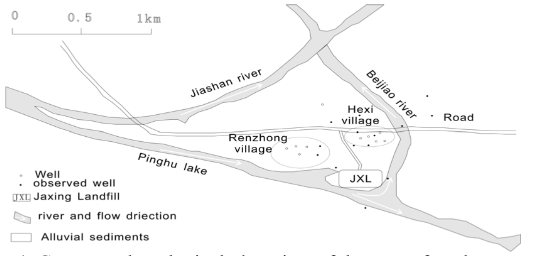

Figure 4. Conceptual geological plan view of the area of study

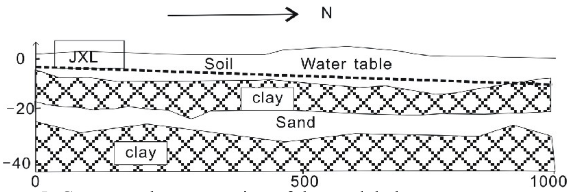

Figure 5. Conceptual cross-section of the modeled area

Table 3. Geological-geotechnical and climatic characteristics

Property	Layer 1	2	3	4
Geologic material	Soil	Clay	Sand	Clay
Hydraulic conductivity (m/d)				
Total porosity	0.32	0.41	0.35	0.39
Effective porosity	0.28	0.21	0.33	0.25
Average thickness(m)	10	10	5	15
Longitudinal dispersivity (m)	0.1	0.01	0.2	0.01
Horizontal dispersivity ratio	0.1	0.01	0.2	0.01
Vertical traverse dispersivity ratio	0.1	0.01	0.2	0.01
Rainfall (mm/year)	1800			
Recharge (mm/year)	600			
Field capacity (m^3/m^3)	0.19			
Storage (l/m)	0.00015			
Bulk density (kg/m^3)	1800			

V. RESULTS AND DISCUSSION

The basic input data for modeling the aquifer parameters includes topography, geometry, elevation, and soil properties of each soil layer in the aquifers. Since the study area is close to a river, the river level was taken as the first boundary. Discharge from the system includes pumping wells and evapotranspiration. A total of 21 village pumping wells located in the study area were taken into consideration. A finite-difference grid was developed to adequately discretize the model domain by minimizing the total number of model cells. For the JXL, the groundwater system of interest is about 1.7 km^2 and is covered with 3D grid cells of D_x=18.25 m, D_y=38.49m consisting of 8,480 cells. Boundary conditions are assigned head boundary to all three sides according to the surface water level. The general head boundary is typically a MODFLOW feature which models the in or outflow to an element through the difference between the head in the element itself and an external fixed head. The Pinghu Lake and Beijiao River in the study area appear to intersect the groundwater system. The river package was applied to account for this feature. In addition, the drain package is used to take into account the features of drained agricultural areas. The average recharge amount from paddy fields to groundwater was estimated to be 8.5millmeter/day during the planting season of crops from June to September. Water levels along the eastern model boundary were designated as a time varying specified head boundary as water entering or leaving the system depends on the water-level gradient between cells in consideration and adjacent active cells. The initial heads were interpolated based on water level data from near by wells. The final choices for model parameters were achieved through trial and error. During the calibration, the hydraulic characteristics of the modeled layers were adjusted until a satisfactory correspondence between model results and observed field data was obtained. Calibrated hydraulic parameters of material properties of the layered aquifer systems are summarized in Table 3. Fig. 6 shows satisfactory calibration of two wells.

According to the results of the computer program, there will be no contamination in observation wells at Renzhong village for a long time. Fig. 7 shows the model area where Chloride ion (Cl^-) (100 mg/l) moves 180m to the north and 30m to the west in the past 10 years in the groundwater. The result of the model indicates that chloride does not reach the observation wells (QR22, QR23) in Renzhong village during this time. But in 30 years, the model results also indicate that Cl^- (100 mg/l) can move about 600 m in groundwater to the north, and most of the wells in Hexi village will be affected. Oil and grease has also been applied on the model area, according to this study oil and grease cannot reach the wells in Hexi village since it degrades and is adsorbed by soil particles in 10 years in the future.

Analysis of the groundwater transport model result indicates that leachate move mainly northwards and eastwards. Part of the wells in Hexi village will be contaminated in 5 years suggesting high amount of contaminant transport into the Beijiao River from the landfill, the Pinghu Lake receives minute quantity of the pollutants.

VI. CONCLUSION

The USGS modular 3D finite difference groundwater flow model (MODFLOW) and Modular 3D Finite Difference Mass Transport Model (MT3D) software were used to simulate groundwater flow and contaminant transport modeling. The contaminant source was attributed to leachate from Jiaxing Landfill contaminating groundwater and eventually wells.It was found that groundwater flow is most sensitive to the changes in the hydraulic conductivity and to a lesser extent to changes in infiltration and leachate infiltration flow. The model calibration was performed with field data of the measured chloride plume.

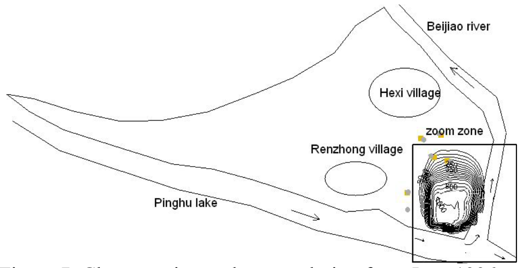

Figure 7. Cl^- contaminant plume evolution from June 1996 to September 2007

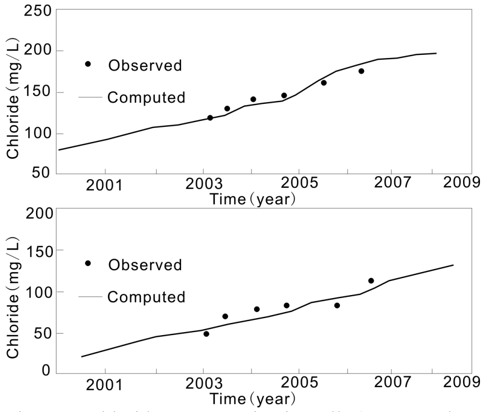

Figure 6. Chloride concentration in wells (QJ823 and QJ817)

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