Journal of Environmental Sciences (*China*) Vol. 4, No. 1, pp. 43 –51 , 1992 ISSN 1001-0742

Study of prediction for groundwater contamination in wastewater land treatment system

Liu Zhaochang, Liu Xiang and Zhu Kun

Department of Environment Engineering, Tsinghua University, Beijing 100084, China

Abstract—This paper uses a prediction model of groundwater pollution based on the experiments in the laboratory and in field . The model , which was tested and calibrated by the field observated data , satisfactorily simulated the field conditions in land treatment system of wastewater . Particularly , the model can provide the reliable pollution prediction of heavy metals , organisms and nitrogen . The model was used to predict the groundwater pollution caused by the land treatment system in the region of North China . The calibration of the model showed that correlation coefficients between the tested and predictive data of Cr^{6+} , As^{3+}, organism and NH_4^+ could reach 0.990, which proved that the model possessed the realistic instructive significance for design and use of wastewater land treatment systems .

Keywords : prediction model ; groundwater pollution ; land treatment system .

INTRODUCTION

In recent decades, the common way of reusing wastewater is agricultural irrigation, especially in the northern China. According to the statistics of the Agricultural Ministry of China, the farm land irrigated by wastewater reached 1.4 million hectares in 1988 and is increasing continuously. The matters of irrigation using pretreated or untreated wastewater are similar to the land treatment systems which are developed in other countries. The long term practices proved that wastewater irrigation was an effective way to lessen water resource shortage, but would promote groundwater contamination if the irrigation management was unsuitable.

Groundwater is the main water resource in China, especially in the northern region, where water supply shortage and water pollution are getting more and more serious, by which the regional economic development is restrained. An investigation indicated that only in North China (including three provinces and Beijing, Tianjin) would lack 3 billion cubic meters of fresh water, additionally, 60% of land and almost entire shallow groundwater were contaminated to various extent. The common pollutants are: hardness, nitrogen (e. g. nitrate, nitrite and ammonium), heavy metals (e. g. Cr, As, Hg, Pb) and phenol and so on. Generally, the wastewater irrigation is the direct or indirect paths for aquifer contamination.

Land treatment technique, being the simple, effective and economical way, is suitable for the actual rural conditions in China, therefore, it will be developed continuously in the northern part of the country. In China, much work has been done on developing technology of wastewater land treatment and improving methods for controlling soil, groundwater and air pollution during 1980s. The typical treatment land was chosen for two-year field experiment to investigate the water quantity balance and the regulations of contaminant migration and transformation. A lot of research reports and papers have been contributed on the basis of laboratory experiments and field tests in Beijing, Shandong, Hebei and Liaoning provinces. Different mathematic models have also been individually developed to simulate the behavior of groundwater in soil and aquifer. Eventually, after the sub-models were examined in the practices, they were combined into a integrated predictive model. Through a long-term observation, the integrated model of wastewater irrigation system has provided an effective and useful tool for managing wastewater irrigation and controlling groundwater pollution.

DIVISION OF FUNCTION UNITS IN LAND TREATMENT SYSTEM

After reacting with soil, micro-organism, plants and soil water and so on, the wastewater which is discharged on land can infiltrated directly into unconfined aquifer. Hence a natural circulation system is formed. According to the transport and transformation characteristics of pollutants, wastewater irrigation system is divided into following units: pollution sources (wastewater), pretreatment facilities, pumping wells, tillage layer (including plough-bottom layer), lower unsaturated zone, and unconfined aquifer and so on. Each unit possesses the special function against contamination (Zhang, 1989). For example, the tillage layer, the most important function layer of the land treatment system, has the highest treatment efficiency because of the aerobic condition and existence of a great amount humus and micro-organism (Liu, 1989).

The processes of research on land treatment system of groundwater pollution are as follows:

(1) Determining the main pollutants and their background values by evaluating of current pollution situation.

(2) Setting up the mathematical sub-models based on the physical simulations of the units.

(3) Predicting pollution effects in actual conditions with the integrated model.

(4) Proposing the countermeasures to prevent soil and groundwater from pollution of wastewater irrigation according to predictive results.

ESTABLISHMENT OF SUB-MODELS

Water flow field simplification

Affected by rainfall, evaporation, irrigation period, field boundary conditions, groundwater flow state, properties of soil and aquifer, the infiltration flow of wastewater in the land treatment system is very comlicated. It is necessary to simplify the flow field in order to analyze its fundamental characteristics. The work is concerned with in three aspects:

(1) Time simplification

The efforts only focus on an average state, i. e. steady state is considered while the fluctuation of hydraulic load is ignored.

(2) Space simplification

According to water content of soil, the whole system is classified into unsaturated and saturated zones whereby the flux equations are established respectively.

(3) Pollutant migration simplification

Because of the complexity of migration ways of pollutants in soils, the chemicals are categorized into mobile form (Cr, As) and residual form (Pb, Cd).

Unit model expression

According to the dominant reactive mechanisms of each layer, the system is divided into three units: tillage layer, lower unsaturated zone and aquifer which are illustrated in Fig. 1.

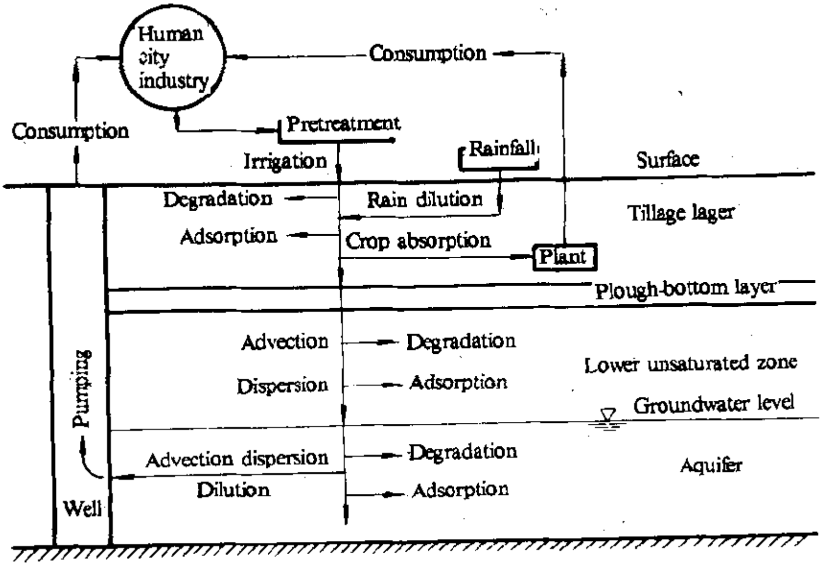

Fig. 1 The layer division of land treatment system

The unit models were developed individually based on chemical dynamics, reaction principles and the previous researches (Javandel, 1985; Aral, 1989; Mclaren, 1971; Wierenga, 1989; Lin, 1988; Travis, 1980; Amoozegar-Fard, 1984; Lue, 1990), then they were tested by the experimental results, and the various models were used to match the several chemical substances.

(1) Models in tillage layer

The tillage layer refers to plowed soil within 30 cm thick where the soil physical properties are complicated, and chemical, biochemical reactions appeare strong. Taking into account the complex physical, chemical and biochemical processes, such as adsorption, biodegradation, plant absorption, advection and dispersion and so on, in surface soil, the predictive models are expressed as Eq. (1), (2) and (3) in which one-dimension advection is concerned when dynamic dispersion is neglected due to the thin soil layer.

For organic compounds:

$$-Rd\frac{\partial C}{\partial t} = v \cdot \frac{\partial C}{\partial z} + (K_o+K_2) \cdot Rd \cdot C , \tag{1}$$

$$Rd = 1 + \frac{\rho}{n} Kd .$$

For heavy metals:

$$-Rd\frac{\partial C}{\partial t} = V\frac{\partial C}{\partial z} + K_2 \cdot Rd \cdot C . \tag{2}$$

For nitrogen, sub-model is a group of the two equations:

$$\begin{cases} -\dfrac{\partial C_{N_1}}{\partial t} = v \cdot \dfrac{\partial C_{N_1}}{\partial z} + (K_1+K_3)(C_{N_1}+\dfrac{\rho S}{n}) + K_2 \cdot C_{N_1} + \dfrac{\rho}{n} \cdot \dfrac{\partial S}{\partial t} \\ -\dfrac{\partial C_{N_2}}{\partial t} = v \cdot \dfrac{\partial C_{N_2}}{\partial z} - K_1 C_{N_1} + K_2 \cdot C_{N_2} . \end{cases} \tag{3}$$

where C : pollutant concentration, g/m^3;

Kd: distribution coefficient, m^3/kg;

D : vertical dispersion coefficient, m^2/d;

v : porous water velocity, m^3/d;

Rd: retardation factor;

ρ : soil bulk density, kg/m^3;

n : soil effective porosity;

S : reaction amount of pollutant, g/m^3;

$\partial S/\partial t$: reaction rate of pollutant, g/m^3/d;

z : vertical axis (positive downward), m;

K_o: biodegradation coefficient, 1/d;

K_1: nitrification rate coefficient, 1/d;

K_2 : plant absorption factor;

K_3 : volatilization coefficien t, g/m^3/d;

K_4 : denitrification rate coefficient, 1/d;

C_{N_1} : NH_4^+-N concentration, g/m^3;

C_{N_2}: NO_3^--N concentration, g/m^3 .

(2) Models for lower unsaturated zone

Parkin *et al.* (1989) concluded that surface tillage practices had little influence on microbial activity below the root-zone. Therefore, the sub-model of unsaturated zone differs from that of the upper soil. Municipal wastewater irrigation is generally considered as a non-point pollution process. Thus a one-dimensional vertical advection-dispersion models are chosen:

For organic compounds:

$$-Rd\frac{\partial C}{\partial t} = v \cdot \frac{\partial C}{\partial z} - D \cdot \frac{\partial^2 C}{\partial z^2} + K_o \cdot Rd \cdot C \,. \tag{4}$$

For heavy metals:

$$-Rd \cdot \frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial z^2} - v \cdot \frac{\partial C}{\partial z} \,. \tag{5}$$

For nitrogen, solution should fit both two equations:

$$\begin{cases} \dfrac{\partial C_{N_1}}{\partial t} = D \cdot \dfrac{\partial^2 C_{N_1}}{\partial z^2} - v \cdot \dfrac{\partial C_{N_1}}{\partial z} (K_1 + K_3)(C_{N_1} + \dfrac{\rho S}{n}) - \dfrac{\rho}{n} \cdot \dfrac{\partial S}{\partial t} \\ \dfrac{\partial C_{N_2}}{\partial t} = D\dfrac{\partial^2 C_{N_2}}{\partial z^2} - v\dfrac{\partial C_{N_2}}{\partial z} + K_1 \cdot C_{N_1} - K_4 \cdot C_{N_2} \,. \end{cases} \tag{6}$$

Assuming water flow in steady state, the flux rate of soil water in lower unsaturated zone is constant. Conceptually, in one-dimension, these transport and transformation mechanisms are relatively well understood for laboratory scale experiments.

(3) Pollutant transport models in aquifer

If natural groundwater inflow were ignored, two-dimension symmetric groundwater flow in cylindrical coordinates under the pumping condition could be written as:

$$Kr \cdot \frac{\partial^2 H}{\partial r^2} + \frac{1}{r} \cdot Kr \cdot \frac{\partial H}{\partial r} + Kz \cdot \frac{\partial^2 H}{\partial z^2} = 0 \,, \tag{7}$$

where Kr, Kz are permeability coefficients in r (radius) and z direction respectively (m/d); H is water head (m).

Based on the water quantity solution of Eq. (7), pollutant transport models are presented as :

For organic compounds:

$$Rd\frac{\partial C}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(Dr \cdot \frac{\partial C}{\partial r}) + \frac{\partial}{\partial z}(Dz \cdot \frac{\partial C}{\partial z}) - v_r \cdot \frac{\partial C}{\partial r} - v_z \cdot \frac{\partial C}{\partial z} - K_o \cdot Rd \cdot C \,. \tag{8}$$

For heavy metals

$$Rd\frac{\partial C}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(Dr\frac{\partial C}{\partial r}) + \frac{\partial}{\partial z}(Dz\frac{\partial C}{\partial z}) - v_r \cdot \frac{\partial C}{\partial r} - v_z \cdot \frac{\partial C}{\partial z} \,. \tag{9}$$

For nitrogen, there is a combination of the two equations:

$$\begin{cases} \dfrac{\partial C_{N_1}}{\partial t} = \dfrac{1}{r}\dfrac{\partial}{\partial r}\left(Dr\dfrac{\partial C_{N_1}}{\partial r}\right) + \dfrac{\partial}{\partial z}\left(Dz\dfrac{\partial C_{N_1}}{\partial z}\right) - v_r\dfrac{\partial C_{N_1}}{\partial r} - v_z \cdot \dfrac{\partial C}{\partial z} \\ \qquad - K_1 \cdot \left(C_{N_1} + \dfrac{\rho}{n}\right) - \dfrac{\rho}{n} \cdot \dfrac{\partial S}{\partial t} \quad ; \\ \dfrac{\partial C_{N_2}}{\partial t} = \dfrac{1}{r}\dfrac{\partial}{\partial r}\left(Dr\dfrac{\partial C_{N_2}}{\partial r}\right) + \dfrac{\partial}{\partial z}\left(Dz\dfrac{\partial C_{N_2}}{\partial z}\right) - v_r \cdot \dfrac{\partial C_{N_2}}{\partial r} - v_z \cdot \dfrac{\partial C_{N_2}}{\partial z} \\ \qquad + k_1 C_{N_1} - K_4 C_{N_2} \end{cases}$$

Where r is radical coordinate, other symbols are the same to the above listed.

Two-dimension models are generally the most useful tools for analyzing and predicting pollutant migration and transformation in field, especially for nonuniform fields. The most common use of 2-D analysis is dependent on monitoring point recharge or discharge explicitly.

VALIDATION OF THE INTEGRATED MODEL

The development and solution of the above sub-models can well reflect pollutant transport and transformation in every individual layer of the soil profiles. In order to solve the partial equations, both finite difference method and finite element method were employed under the given initial and boundary conditions (Zienkiewicz, 1976). For example, the solution of a partial difference equation could be transformed into solving a group of linear algebraic equations expressed by a tri-diagonal matrix using trace-back method.

The integrated model is formed from the combination of the sub-models listed above, i. e. coupling Equation (1) to (10). The integrated model enables us to obtain pollutant distribution in the entire irrigation system and to simulate the migration and transformation processes in each classified layer as well.

PARAMETER DETERMINATION

The parameters used in calculation were derived from the results of a series of simulation tests in field or laboratory while the boundary conditions used in modelling were generalized from the prevailing conditions of wastewater irrigation areas. If condition not permitting, somehydrodynamic coefficient, such as dispersivity and porosity, can also be obtained the similar experimental data. By the history reappearing method, the calculated parameters were put into the computer program for repeating calibration until the result matched with the observation data pretty well.

MODELLING CALIBRATION

After setting up the integrated model, it was necessary to check the reliability of the predictive results through the tested data. Here is presentation of some practical examples.

Example 1: In unsaturated column test, sand with the bulk density 1.57 was packed 73 cm thick. The neutron isotope (tritium) solution was distributed on top soil with the rate of 2.41 L/h lasting two hours for every 4 days. In the unsteady flow, the variation of indicator concentration were measured at the outlet 50 cm deep. The comparison between the observed data and predictive curve is showed in Fig. 2.

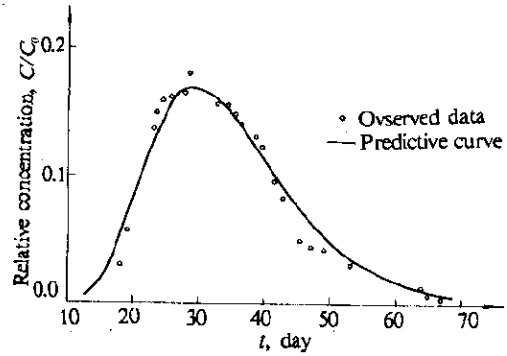

Fig. 2 Comparison between predictive results and observed data in column test of stable flow

Example 2: The organic pollution prediction was proceeded in the Shenyang wastewater land treatment system. Organic concentration presented by COD, BOD and TOC values. After putting the analyzed parameters, initial and boundary conditions into the integrated model, the computer programs calculated the accumulating quantities of organic compounds in tillage layer and lower unsaturated zone for 100-day wastewater irrigation. The model showed the reliable results in 6 spots of the total 7 observation spots with only one exception which was made by a fracture in soil. The predictive consequences are diagramed in Fig. 3.

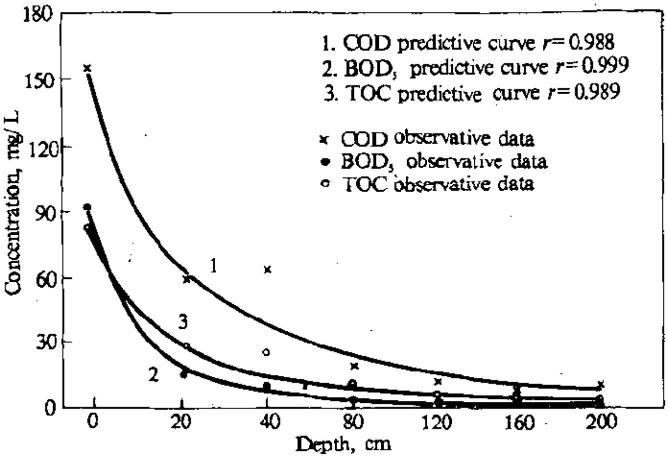

Fig. 3 Comparison of organic concentrations between observation and prediction

(1) COD predictive curve, $r=0.988$

(2) BOD_5 predictive curve, $r=0.999$

(3) TOC predictive curve, $r=0.989$

Example 3: In order to check the reliability of the integrated model to predict the pollutant mobility in multiple layers, the history recurrence calculation was proceeded based on the 20-year observed data in the Fen River irrigation area, Shanxi Province. After determining parameters, putting the initial and boundary conditions into the computer programs, the integrated mathematic model calculated the current groundwater qualities which then compared to the actual observed data. The comparison results can be seen in Table 1.

Table 1 Comparison between the observed and predictive groundwater concentrations in the Fen River irrigation area

Pollutants	Data source	Upper reaches	Middle reaches	Lower reaches
Cr,	Observed	0.005 – 0.02	0.005 – 0.04	0.001 – 0.02
mg/L	Predicted	0.021	0.026	0.019
As,	Observed	0 – 0.01	0 – 0.01	ND
mg/L	Predicted	0.0043	0.0044	0.0035

Comparing the two groups of data, it was conformed that the matching tendency was satisfactory. The predictive data approached to the upper limits of the observed data because groundwater flux was assumed to be steady state. Another reason for divergence between the observed and predicted data was that the aquifer was neither uniform, nor isotropic and the natural inflow of groundwater was changeable, too.

In practice, the repeating tests were conducted for the different initial concentrations in the processes of investigation. Finally, the optimum selections for pollution control would be analyzed based on the calculation results. Definitely, the integrated model is a powerful tool for simulating and predicting groundwater pollution arisen from wastewater irrigation.

CONCLUSION

The systematic planning method is used in this paper to study the effects of the major pollutants, such as heavy metals, nitrogen and organic substances, on the groundwater qualities in land treatment system of wastewater. The integrated mathematic model can predict the groundwater pollution situation at any time or determine the deadline when the groundwater quality is beyond the limit for drinking. Through examining and utilizing , the model was proved to be a powerful tool for instructing the design of land treatment system. In addition to determing the reasonable hydraulic and pollutant loads, the model can provide the theoretical support for the scientific management of wastewater land treatment system for the purpose of treating and reusing wastewater, protecting groundwater resources. This method can be applied for controlling groundwater pollution caused by pesticides, chemical fertilizers, and solid wastes as well.

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(Received April 3, 1991)