Lead contamination of groundwater in the northeast of Buenos Aires Province, Argentina

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Abstract The progressive increase of water needs due to the expansion of urbanization and industrialization in different regions in the northeast of Buenos Aires Province, Argentina has resulted in intensive development of the groundwater resource. The main objective here is the study of two sectors of different hydrogeological features that have been contaminated by lead from industrial activities. We employ a method of characteristics combined with a mixed finite element procedure to simulate the plume evolution in time. The outcome of this investigation is the application of an efficient tool for handling water resources and evaluating the environmental impact from the transport of contaminants in groundwater.

Key words groundwater; lead contamination; northeast of Buenos Aires Province, Argentina; numeric simulation; shallow aquifer

INTRODUCTION

Detailed description of the migration of pollutants is fundamental to groundwater monitoring and represents the basis for the preservation of groundwater resources. An important problem is the increasing contamination of groundwater, which in turn, leads to a decrease in the availability of good quality water. Contamination dramatically affects the regional behaviour of the shallow groundwater system located in the northeast of the Province of Buenos Aires, Argentina.

In this paper we assess the variability of solute migration by augmenting historical data with groundwater sampling for water quality analyses and hydrogeological investigations. Recent reports reveal contamination of soil and groundwater with heavy metals, and in particular, show lead concentrations that may be so high as to be toxic to living organisms. Lead can damage human health, especially through disruption of the functions of the brain, kidneys and reproductive system. The body accumulates lead in the blood, bones and teeth, and soft tissue. Lead is absorbed through ingestion, inhalation, or other exposures.

There are many sources of lead in this environment including paint, gasoline, water distribution systems, food, and various hobby supplies. The lead is transported to the environment by atmospheric deposition, and solid and liquid waste disposal. Groundwater receives lead contamination by mobilization of lead in soil, present either naturally or as a result of anthropogenic activities, and in some cases due to mineral weathering. The US Environmental Protection Agency (USEPA) current drinking water lead standard is 0.015 mg l^{-1}. The USEPA lead standard is used in Argentina as a tolerable limit for drinking water.

The transport of a reactive solute in spatially variable soil systems, and in particular the effect of the spatially variable hydraulic properties on solute transport were studied by Van der Zee & Van Riemsdijk (1987). Marzal *et al.* (1994) presented a coupled transport-chemistry hydrogeochemical model, which can predict the development of contamination plumes. The linear isotherm model combined with a convective–dispersive solute transport model have been used frequently to describe the transport of material through porous media. Begovich & Jackson (1975) used a linear adsorption isotherm for lead. Chen *et al.* (1992) studied adsorption of cadmium, copper, and lead in the presence or absence of the other two elements, at five concentration levels. Adsorption of lead and other heavy metals by soils and the transport has been studied by many authors (e.g. Griffin & Au, 1977; Farquhar *et al.*, 1997).

In this paper, two field experiments conducted in the shallow groundwater system of the northeast of Buenos Aires Province, Argentina, during 1999, to investigate the transport of lead contaminated water through the saturated zone, are described.

Using hydrogeological data from pumping tests, we constructed the hydraulic conductivity field, which was used in a numerical model to obtain the groundwater flow field. The flow field was used to simulate lead transport through the saturated zone. The hydraulic conductivity is affected by the heterogeneity of the aquifer. The field hydraulic conductivity measurements were kriged to generate the spatial distribution of hydraulic conductivity.

The advection–diffusion equation was used to describe the spatially variable vertical lead transport using a method of characteristics combined with a mixed finite element procedure, which provides an efficient way to eliminate spurious numerical oscillations and handle the convective term in the equation.

MODEL

Hydrogeological characteristics of the areas study

The shallow groundwater system includes the Puelche, Pampeano and Postpampeano hydrogeological units.

The Pampeano unit is located in high plains and the Postpampeano unit is in low plains. Each unit includes the water table, and the associated groundwater is directly affected by processes originating at the surface (infiltration and contamination). Both units overlie the Puelche unit, which is the main aquifer of northeast Buenos Aires Province. In the study area, the Puelche unit is located at a depth of about 40 m, is up to 20 m thick and is composed by fine to medium sand.

The Pampeano unit is composed of silty sediments, in part clayey and sandy with calcareous materials. The unit is locally anisotropic, which affects production and associated abstraction rates. The Pampeano unit is about 40 m thick having a regional transmissivity of 100 m^2 day^{-1}. The Postpampeano unit is composed of silty clay, clay, and clayey silt, and varies in thickness from 3 to 7 m with a hydraulic conductivity of 0.01 m day^{-1}. The shallow groundwater systems (Puelche, Pampeano, and Post-pampeano) are hydraulically connected and constitute a "multilayer aquifer".

The groundwater lead concentration in non contaminated areas of the Pampeano and Postpampeano units is about 0.003 mg l^{-1} (Galindo *et al.*, 1999). The highest lead concentrations (0.10 mg l^{-1}) were in shallow groundwater in industrial areas. For this study, two field sites in these industrial areas were chosen to simulate the evolution of the plume of lead contamination, one in the Pampeano unit and the other in the Postpampeano unit.

Solute transport equations

The transport equation for lead was derived from the law of conservation of mass applied to a differential volume element in the porous medium. The accumulation of the contaminant is exclusively caused by convective–dispersive transport and can be written as:

$$\phi \frac{\partial C(x,t)}{\partial t} + \nabla \cdot (\mathbf{D} \nabla C(x,t)) - \mathbf{q}_w \cdot \nabla C(x,t) = 0 \quad x \in \Omega \tag{1}$$

where $C(x,t)$ denote the mass concentration of the contaminant at location x, $\mathbf{q}_w$ the flux velocity vector, Ω the two-dimensional porous domain, ϕ the porosity and $\mathbf{D}$ the dispersion tensor. To fully define the system mathematically, initial and boundary conditions must be specified. The initial condition is defined by specifying the total concentrations of the solute at time zero throughout the transport domain. The flow satisfies Darcy's law and under the incompressibility assumption, we have:

$$\nabla \cdot \mathbf{q}_w = 0 \tag{2}$$

The modelling technique is based on a discrete representation of the porous medium. The stationary velocity field is computed using a hybridized mixed finite method and small variations in groundwater flow directions were found.

The transport equation is solved numerically by combining a method of characteristics with a mixed finite element procedure (Douglas & Russel, 1982; Douglas *et al.*, 1995), which is used to eliminate the nonsymmetry in the operators due to advection.

Lead adsorption

The heterogeneous characteristic of the porous medium and the sorption in soil influence the solute transport. When chemical species are dissolved in groundwater they may adsorb on the surface of porous media, which can be modelled by either linear or nonlinear isotherms. The simplest and most widely used of the equilibrium sorption isotherms is a linear isotherm. That is, it is assumed that the amount of the solute adsorbed by the soil matrix and the concentration of the solute in the soil solution are related linearly. Taking adsorption into account, the mass balance equation becomes:

$$\frac{\partial(\phi C(x,t) + \rho S(x,t))}{\partial t} + \nabla \cdot (D \nabla C(x,t)) - q_w \cdot \nabla C(x,t) = f(x,t) x \in \Omega \tag{3}$$

In equation (3) ρ denotes the bulk density of the soil and S is the adsorbed concentration. In this study we consider a linear adsorption isotherm of the form:

$$S(x,t) = k_d C(x,t) \tag{4}$$

where k_d is an empirical distribution coefficient and it is a measure of retention of solute by the soil matrix.

RESULTS

Application examples

The model was used to simulate lead transport in the two hydrogeologically different settings: the Pampeano and Postpampeano units. In each unit, however, lead concentrations greater than 0.05 mg l^{-1} have been recorded for water sampled from wells, indicating the existence of contamination. We analysed the lead concentration variations in two 10×5 m sections of the saturated zone for each unit. The initial condition for the lead contamination was $C_0 = 0.05$ mg l^{-1} at the top of each section (depth $z = 0$ m) located at $x = 3$ m in the horizontal direction. In all the simulations the following parameters were use: $\Delta x = 1$ m, $\Delta z = 0.25$ m, $\Delta t = 1$ day, $k_d = 0.2536$ mmol kg^{-1} (Houng & Lee, 1998), and the calculations were obtained for a 5-m depth of saturated soil profile. For the Pampeano unit, the hydraulic conductivity ranged from 1 to 10 m day^{-1} with a porosity (ϕ) = 0.2, and for the Postpampeano unit, the hydraulic conductivity ranged from 0.01 to 0.1 m day^{-1} with $\phi = 0.4$.

In the first case, the concentration maximum migrates 1 m horizontally from the contaminated point after 30 days (Fig. 1), and the zone of maximum concentration continues to move at the top of the saturated zone. After 60 days the concentration maximum also moves vertically to 0.25 m below the initial depth of contamination (Fig. 2). The temporal concentration profile development under the initial point of contamination is shown as a function of the depth in Fig. 3.

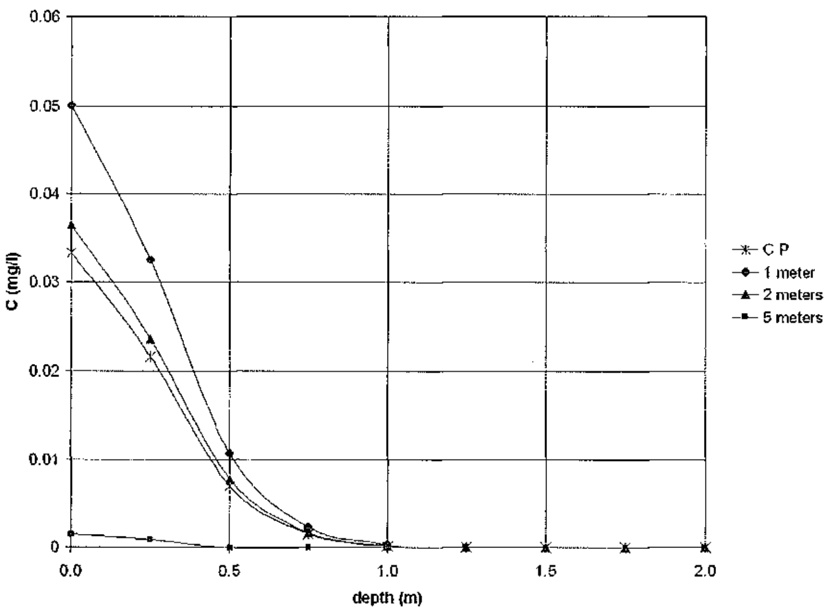

Fig. 1 Lead concentration profile at time t = 30 days at several distances from the point of contamination (CP) in the Pampeano unit.

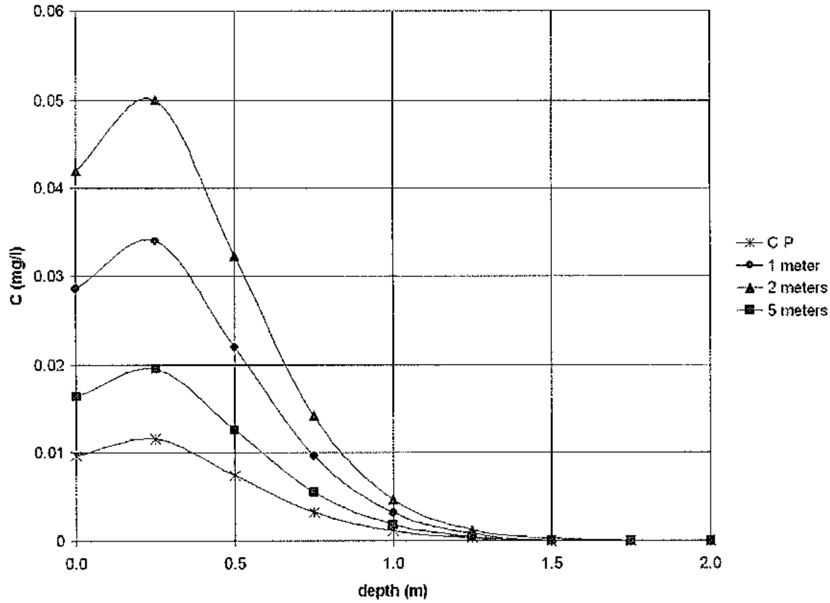

Fig. 2 Lead concentration profile at time t = 60 days at several distances from the point of contamination (CP) in the Pampeano unit.

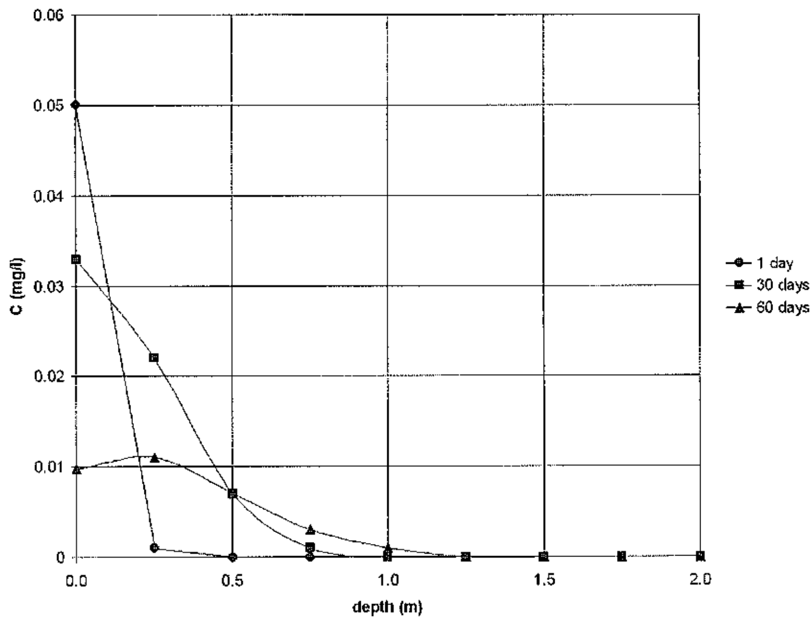

Fig. 3 Lead concentration profile at various times at the contaminated point for the Pampeano unit.

In the medium of lower hydraulic conductivity, the Postpampeano unit, the lead does not migrate appreciably, mainly due to the low groundwater velocity (Fig. 4). After 400 days, lead does not move more than 1 m (Fig. 5).

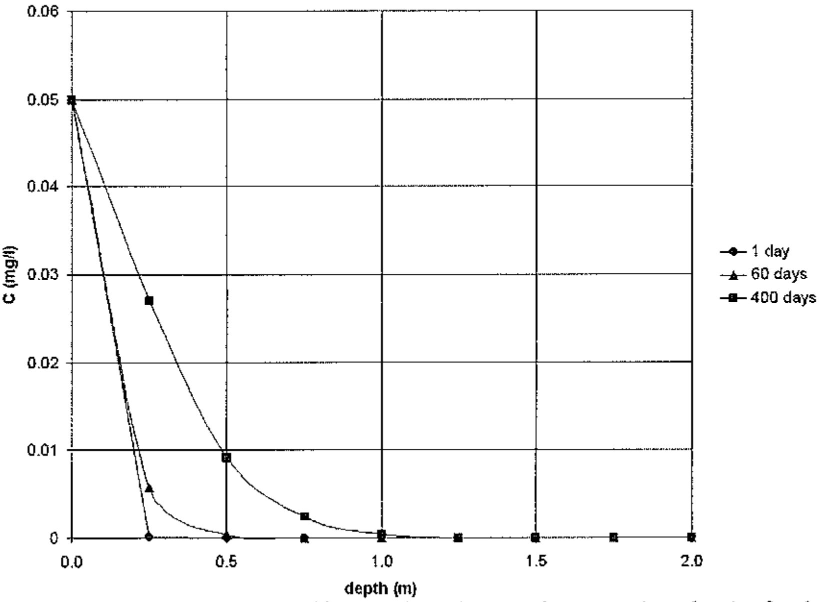

Fig. 4 Lead concentration profile at various times at the contaminated point for the Postpampeano unit.

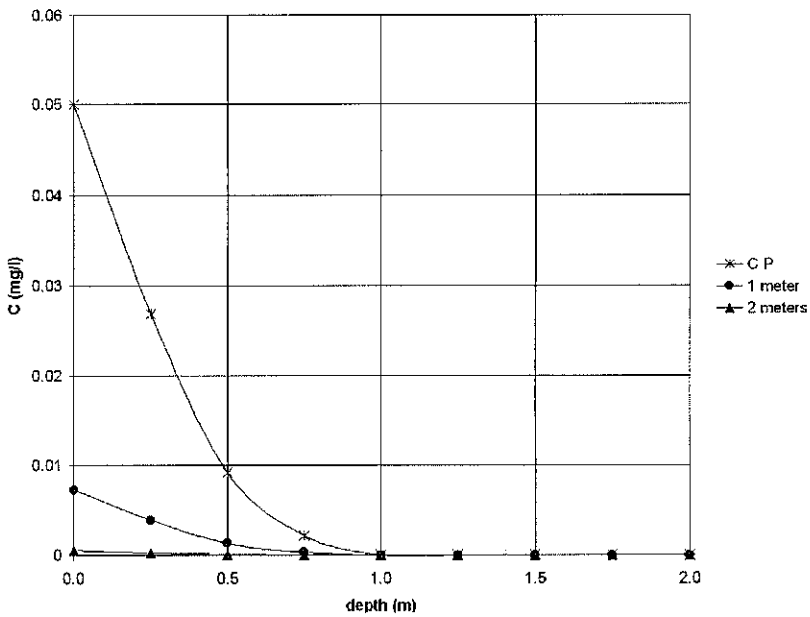

Fig. 5 Lead concentration profile at time t = 400 days at two distances from the point of contamination (CP) in the Postpampeano unit.

CONCLUSIONS

Model simulation of groundwater lead migration demonstrates that the hydraulic conductivity and porosity are important controls in the shallow groundwater system of the northeast of the Province of Buenos Aires, Argentina. The migration of lead in the Postpampeano unit is very slow and the movement is minimal. The possibility that significant amounts of lead would reach the main aquifer (Puelche), which underlies the Postpampeano unit, would only occur along macropore features like fractures or spatial heterogeneity of hydraulic conductivity, such as fine lenses of sand.

The migration of lead in the Pampeano unit is slow, but mobility is higher than in the Postpampeano unit and may in time affect the potable groundwater supplies in the region.

The examples presented here illustrate that solute transport can be predicted for different hydrogeological conditions and the predicted transport may be used to plan different remediation strategies.

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