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NUMERICAL MODELING FOR RISK ASSESSMENT OF GROUNDWATER CONTAMINATION UNDER RIVER AND PUMPING EFFECTS

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The two-dimensional groundwater flow and contaminant transport model is designed to support the analysis of a pathway of chlorinated hydrocarbons in a subsurface contaminated site. The proposed modeling approach employs hypothetical scenarios and demonstrates a capability to narrow down uncertain occurrences at the site. Modeling results show a comparison between chlorobenzene distribution in the absence and the presence of a river. Two observation wells indicate that on average 50 and 70 % of the concentration seeps out to the river from the aquifer, leading to contaminant spreading downstream. In addition, the flow and transport of contaminants at the site have been affected by pumping. Modeling estimated that more than 90 % of the contaminant concentration observed in three wells was reduced after 3 years of operation at four pumping wells during 2001 to 2003. This suggests that a high efficiency of multiple pumping techniques can prevent more migration of contaminants. On the other hand, it was shown that the part of the plume that extends more than 130 m downstream of the source cannot be captured by the current pumping since the predicted transport path is beyond well capture zones. It is concluded that a numerical approach using hypothetical scenarios can serve as a useful preliminary attempt to reconstruct the history of contaminant release. It can estimate the future pollutant distribution, in particular when observation data is insufficient.

INTRODUCTION

Subsurface contamination by chlorinated hydrocarbons is common throughout many areas of North America, Europe, and Asia. Most of these compounds, which are classified into alkyl halides-aliphatic and aryl halides-aromatic, are categorized as persistent organic pollutants (POPs). They are generally considered as long-lived organic compounds that become concentrated as they move through the food chain, exhibiting toxic effects on animal reproduction, development, and immunological function (Andriaens and Gruden, 2004). Based on a comprehensive inventory of the types and sources of chemical contamination in the environment, Swoboda and Cloberg (1995) identified the petrochemical and pesticide industry as the main sources of aryl halides (e.g. dioxins, PCBs). Other common sources of groundwater contamination include the herbicide and wood treatment industry, which use simple aromatic compounds (e.g., chlorobenzenes, chlorophenols) and their derivatives.

Risk assessments are routinely performed at contaminated sites in areas of widespread environmental contamination, such as an entire aquifer, as a means of quantifying the potential threats to public health and ecosystems. The US National Academy of Science and the US EPA have defined four steps in the assessment of risk from hazardous waste (US EPA, 1989a; NAS, 1983): (1) hazard identification (source analysis), (2) exposure assessment (pathway analysis), (3) toxicity assessment (receptor analysis) and (4) risk characterization.

Subsurface contaminant transport models which simplify complex processes are commonly used for exposure assessment (pathway analysis) to determine the concentrations of contaminants that reach the exposed receptors. Practitioners and scientists have recently paid much attention to this tool for supporting an appropriate monitoring and remediation strategy. This is because of a variety of inherent uncertainties pertaining to hydraulic properties, and contamination mechanisms and behaviors frequently found at contaminated sites throughout the world. Typically these problems are compounded by a lack of adequate data.

The objective of this study is the development of a groundwater flow and solute transport model for assessment of spatial and temporal contaminant distribution in the groundwater system polluted by chlorinated hydrocarbon underneath O. river, O. City. The contaminant transport of interest in this study is the aqueous-phase of chlorobenzene which can be a carrier of dioxins. The modeling approach has attempted to reveal the effect of a wide range of processes on the distribution of contaminants. The paper encompasses the integration of a conceptual contamination model, selected simulation scenarios and a variety of numerical methods expected to narrow down significantly the uncertain occurrences in the contaminated site, particularly in situations when the availability of data is limited. The role of the river in the transport of contaminants and the effect of pumping activities on the development of the concentration plume is discussed. Moreover, various pumping scenarios to clean up the site are simulated and evaluated.

DESCRIPTION OF THE SITE

The study site has an area of approximately 1 km^2 and the meandering O. river passes through its central part. The central part of the area is generally flat and the elevation of the alluvial plain along the river ranges from 4.5 to 6 m above mean sea level (m.s.l). To the northeast and the southeast, the land surface rises slightly, whereas it gently declines to the west towards the sea. A massive formation of sandstone creates extremely steep topography in most of the south, a small part of southeast and a small part of the southwest borders. The land elevation of the sandstone area ranges from 15 to 30 m above m.s.l.

Geology and groundwater hydraulics of the site

Geologically the contaminated site is composed of four alluvial layers: silty clays (2.3 m), sands (3.7 m), silty clays (5 m), and sands (5 m). Investigation in the first and the second layer are emphasized since the groundwater flow and the transport of contaminants most probably take place in those layers. The groundwater flow is most likely to occur with a direction parallel to the flow of the central portion of the river from southeast towards northwest. The river flow subsequently bends to the northwest direction. The survey done by the Fukuoka Prefectural Government (2003) indicated that the river position had been significantly changed twice and its present position has existed since approximately 1935. A hydraulic equilibrium between the river and the underlying aquifer since then has likely occurred.

The structural properties of the aquifer in the area of interest (i.e. size, position, and amount of clay lenses, sand and gravel layers, and resulting heterogeneous distribution of hydraulic conductivity and porosity) significantly controls groundwater flow and the migration of solutes as is common in most aquifers (Liedl and Ptak, 2003).

Contamination conceptual model of the site

Hazardous waste problems are frequently generated by mixtures of complex waste that have been disposed on land and have migrated through the subsurface. The most common practice in assessing the risks is to screen the contaminants and pathways using surrogate analysis (US EPA, 1989a). The two most important source characteristics used in that screening are the contaminant concentrations and toxicities.

The detailed investigation of contamination in O. river revealed the presence of dioxins, polychlorinated biphenyls (PCBs), chlorobenzene (CB), pentachlorophenol (PCP) and polycyclic aromatic hydrocarbons (PAHs) in the soil under the riverbed concrete (Fukuoka Prefectural Government, 2003). Even though the river bed was covered with concrete to prevent river contamination from groundwater, the pollutants seeped out to the river. Since the data indicated that dioxins were the most toxic and CB was the most concentrated contaminant in the contaminated sites, the pathway and fate of those compounds are the main interest in this study.

Commonly in soils and sediments where advective fluid flow is minimal, migration of halogenated/chlorinated hydrocarbons is governed by diffusion, whereas in groundwater systems both advection and diffusion processes are operative. Field measurements for adsorbed compounds in sediments indicate that transport of even the most soluble components is on the order of decades long time frames for centimeter distances (i.e., Gevao et al., 1997; Zhang et al., 1999). Meanwhile, Wiedemeier et al. (1999) suggested that in low organic sandy/silty groundwater aquifers, advection transport, in combination with substantial longitudinal dispersion and sorption mechanisms, controls the movement of chlorinated/halogenated hydrocarbons (dioxins, PCB, CB, etc.) on the order of centimeters per day. Subsequently, the numerical study of Kurniawan and Jinno (2006) gave evidence that due to their extremely high hydrophobicity, dioxins and PCBs are most likely to strongly reside on the soil material instead of migrating downwards once they are introduced into a subsurface system. The decreased concentration of the more chlorinated dioxins associated with the increased concentration of the less chlorinated dioxins along the depth of two different soil materials cannot be reproduced by the vertical transport model. This is due to a low solubility of dioxins and a high fraction of organic carbon in the porous material on the study site. The simulated apparent velocity of octachlorinated dioxins (OCDD) was 5.5×10^{11} times slower than the pore water velocity.

The measured data show a positive correlation between the concentration profile of dioxins and PCBs with that of CB (Fukuoka Prefectural Government, 2003). According to Chappelle (1993) the relatively low octanol-water partition coefficient of CB indicates that it tends to be fairly mobile. We postulate that the existence of CB can inevitably enhance the mobilization of dioxins and PCBs from the top of the first layer to the second layer followed by a horizontal transport downgradient. Figure 1 illustrates the concept of how contamination occurs in the study area.

Moreover, CB and polychlorinated benzene have been shown to be biodegradable under aerobic conditions. Several studies have shown that bacteria are able to utilize CB and other less chlorinated compounds such as DCE, 1,2 – DCA, CB, or vinyl chloride as primary growth substrates for microbial metabolism in aerobic systems at a variety of CB-contaminated sites, but not at uncontaminated sites (US-EPA, 1998).

MODELING METHODOLOGY

Mathematical model and numerical solution

The fundamental equation for the horizontal confined aquifer is presented as follows (Bear and Verruijt, 1998; Jinno, 2000):

$$S_0 \times B\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(Bk\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Bk\frac{\partial h}{\partial y}\right) - \sum Q_m \delta\left(x - x_m\right)\delta\left(y - y_m\right) + q_w(x,y,t) - q_r(x,y,t) \quad (1)$$

where S_0 is the specific storage coefficient, B is aquifer thickness (L), k is the hydraulic conductivity (LT^{-1}), h is the piezometric potential (L). The term $Q_m(x,y)$ (L^3T^{-1}) is the water extraction rate by pumping at location (x_m, y_m) at time t. The delta functions $\delta(x - x_m)$ and $\delta(y - y_m)$ represent the location of the pumping well, the term $q_w(x,y,t)$ (L^3T^{-1}) reflects the groundwater recharge and the term $q_r(x,y,t)$ (L^3T^{-1}) expresses groundwater discharge to river. The groundwater discharge to the river is obtained using this following equation:

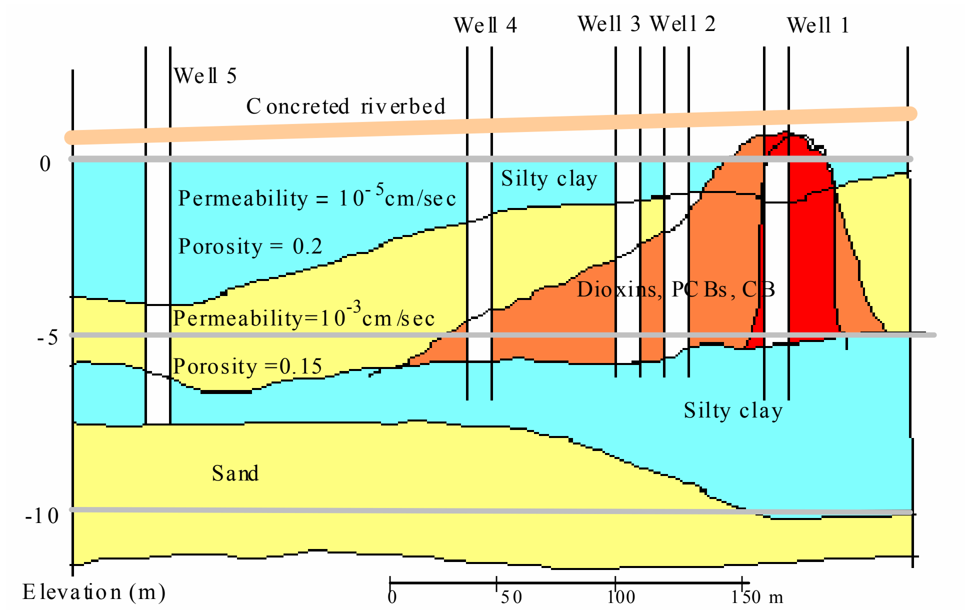

Figure 1. Illustration of contamination conceptual model.

$$q_r = -k_s \frac{h_r - h}{l} \tag{2}$$

where k_s, h_r and l denote the hydraulic conductivity of the silty clay layer (LT^{-1}), riverbed elevation (L) and thickness of the impermeable layer (L), respectively. The seepage from groundwater to the river takes place when the elevation of the riverbed is lower than the piezometric head of the surrounding groundwater. In this research, k_s of 10^{-5} and various l values used were obtained from the geological investigation done by the Fukuoka Prefectural Government (2003).

The governing mass transport equation in the two-dimensional coordinate system is expressed as follows:

$$\frac{\partial C}{\partial t} + \frac{U'}{R_d}\frac{\partial (C)}{\partial X} + \frac{V'}{R_d}\frac{\partial (C)}{\partial Y} = \frac{1}{R_d}\frac{\partial}{\partial X}\left(D_{XX}\frac{\partial C}{\partial X} + D_{XY}\frac{\partial C}{\partial Y}\right) + \frac{1}{R_d}\frac{\partial}{\partial Y}\left(D_{YX}\frac{\partial C}{\partial X} + D_{YY}\frac{\partial C}{\partial Y}\right) - \frac{\lambda}{R_d}(C) \tag{3}$$

where C is concentration of the pollutant (ML^{-3}), D is the hydrodynamic dispersion coefficient (L^2T^{-1}), U' is pore velocity (LT^{-1}) in the X coordinate direction, V' is pore velocity (LT^{-1}) in the Y coordinate direction, λ is first-order decay rate (T^{-1}) and R_d denotes retardation factor.

The dispersion term in two dimensional coordinate systems is formulated as follows:

$$D_{h,xx} = \frac{\alpha_L u'^2 + \alpha_T v'^2}{q'} + \tau.D_m, D_{h,xy} = \frac{(\alpha_L - \alpha_T)u'v'}{q'} + \tau.D_m, D_{h.xx} = \frac{a_L v'^2 + a_T u'^2}{q'} + \tau.D_m \tag{4}$$

where q'= $\sqrt{(u')^2 + (v')^2}$, and α_L , α_T , τ , and D_M are longitudinal dispersivity, transversal dispersivity, tortuosity and molecular diffusion coefficient, respectively. The longitudinal dispersivity value used in this study is 1000 cm which is 10 % of the presumed importance distance, while α_T= (1/10), α_L is usually assumed. Tortuosity is considered equal to 1, whereas the molecular diffusion coefficient is equal about 10^{-5} cm^2/sec.

The retardation factor accounting for the delay of contaminant transport (R_d) attributed to the sorption into soil material or sediment is incorporated (after Appelo and Postma, 2005) using the following equations:

$$R_d = 1 + K_d\left(\frac{\rho_b}{\theta}\right) \tag{5}$$

$$K_d = K_{oc}.F_{oc} \tag{6}$$

$$\log K_{oc} = \log K_{ow} - 0.35 \tag{7}$$

where R_d, K_d, K_{oc}, $K_{ow,k}$, ρ_b, θ, and F_{oc} denote retardation factor of the k-th species, the distribution coefficient (L^3M^{-1}) that depends on the solute species, the octanol-carbon partitioning coefficient and the octanol-water partitioning coefficient of the species, the bulk density of the sediment i.e. the ratio of mass of dried soil to total volume of the soil in ML^{-3}, porosity, and the fraction of organic carbon, respectively.

A first-order decay rate constant, which is one of the most commonly used expressions for representing the biodegradation of an organic compound by applying a half-life term for the chemical, is used:

$$t_{1/2} = \frac{0.693}{\lambda} \tag{8}$$

where $t_{1/2}$ denotes the half-life of the contaminant of concern. Literature values for the half life of CB range 0.02 to 2 years (ASTM, 1995; Howard et al., 1991).

The contaminant transport model developed in this study represents the transport of only the aqueous phase of chlorinated organic compounds. Thus a transformation of the aqueous phase of those species from the measured concentration (adsorbed-phase concentration) was necessary. The following equilibrium equation is applied:

$$\widetilde{C} = K_d . C \tag{9}$$

where C is the aqueous-phase concentration of the species (ML^{-3}), $\widetilde{C}$ is the solid-phase concentration of the species (MM^{-1}).

A combination of Implicit Finite Different Method, Successive Over Relaxation Method and Crank-Nicholson Scheme were employed to solve Equation (1) (e.g. Bear and Verruijt, 1998; Nakagawa et al, 2000). Equation (3) is solved applying the Method of Characteristics (MOC) (Konikow and Bredehoeft, 1978; Kinzelbach, 1986; Konikow et al., 1996; Zeng and Wang, 1999; Jinno, 2001).

Simulation technique

An area of 1300 x 800 m of sandy confined aquifer was discretized by 5 x 4 m cells which accounts for a 260 x 200 grid. The fixed boundary conditions of the piezometric potential on the west and east sides were maintained, whereas a no flow boundary condition was assumed for the other sides. For the massive sandstone area very low permeability was assigned. The porosity was assumed to be uniform within the model area. Due to the lack of available data, the potential head gradient used in this simulation was assigned according to site topography, borehole surveys and field observation. The interaction between the river and groundwater was considered by incorporating the seepage term from groundwater into the river.

At the first simulation scenario, the steady state of horizontal flow and transport simulation in a confined aquifer was conducted assuming the river was absent in the model domain. The second simulation scenario reflected the natural condition. It aimed to analyze the river effect on contaminant distributions. The third simulation scenario included the effect of pumping. The comparison of the second and the third simulations was eventually used to evaluate the consequences of pumping. Table 1 shows the parameters used in this study.

The authors previously conducted a one-dimensional simulation for the vertical transport of CB using MOC (Kurniawan and Jinno, 2006). It was shown that CB carrying dioxins would pass through two different soil materials where silty clay and sand dominate the first and the second layer, respectively. The processes considered in this simulation were advection, dispersion and

Table 1. Simulation parameters.

Parameters	Unit	
Thickness of sand layer	cm	370
Porosity (θ)	-	0.15
Saturated permeability of sand	cm/sec	1.0E-3
Grain size of sand	cm	9.0E-03
Molecular diffusion coefficient (D_M)	cm^2/sec	1.0E-05
Longitudinal dispersivity (α_L)	cm	1000
Transversal dispersivity (α_T)	cm	100
Fraction of organic carbon content (F_{oc})	%	0.16
Soil density (ρ_{soil})	g/cm^3	2.645
Bulk density (ρ_b)	g/cm^3	2.5
Octanol-water partitioning coefficient of CB (log K_{ow})	-	2.84
Retardation factor of CB (Rd)	-	18
Model area	km^2	1.04
Time increment	day	4
Maximum simulation time	year	50
Grid size in X direction	cm	500
Grid size in Y direction	cm	400
Grid number in X direction	-	261
Grid number in Y direction	-	201

adsorption. The 1-dimensional simulation for vertical transport showed evidence that the density difference between pollutants and fresh water was the main driving force for the vertical migration of contaminants. Accordingly, F_{oc}, mass flux rate and period were the influential parameters on the transport and fate of contaminants. That simulation assumed that a CB mass flux of 0.08 ng/cm^2 sec was continuously released for 45 years, from 1930 until 1975, while transport has been occurring up to the present. However, the deviation between the calculated and measured CB was pronounced, which most probably resulted from the pumping activities undertaken to clean up the site. The 1-dimensional vertical transport was modified by incorporating biodegradation in the present study. The time series of CB concentration for 80 years of transport (1930-2010) obtained from that simulation is shown in Figure 2.

In this study, a 2-dimensional horizontal transport simulation was executed by inputting CB concentration from the 1-dimensional simulation as soon as the assumed significant amount of CB concentration arrived at the bottom of the second layer. It was predicted that CB could reach the bottom of the sand layer in 1960 after 30 years of transport from the time the pollutant was first released. The concentration from the 1-dimensional simulation was used as a fixed – time dependent boundary condition for the 2-dimensional contaminant transport simulation. This boundary type took into consideration the pattern of pollutant concentration behavior over time in which the peak of the concentration reached the bottom after 75 years of transport (2005) and declined afterward (see Figure 2). The grid mesh at (140,100) in the 2-dimensional simulation was assumed as the suspected contaminant point source based on the analysis of the local government reports showing that the highest concentrations of all pollutants were detected at that point.

RESULT AND DISCUSSION

The maximum period of horizontal transport simulation in this study is 50 years (from 1960 to 2010) which aims to trace the history of pollutant distribution and to estimate the future plume development throughout the model domain.

Even though the literature claims CB half-life is in the range of 0.02 to 2 years, the higher result occurred when a 2 year half-life was used, and this can be seen by the relatively small plume shown in Figure 3. The uncertainty in the biodegradation process was approximated by using a smaller

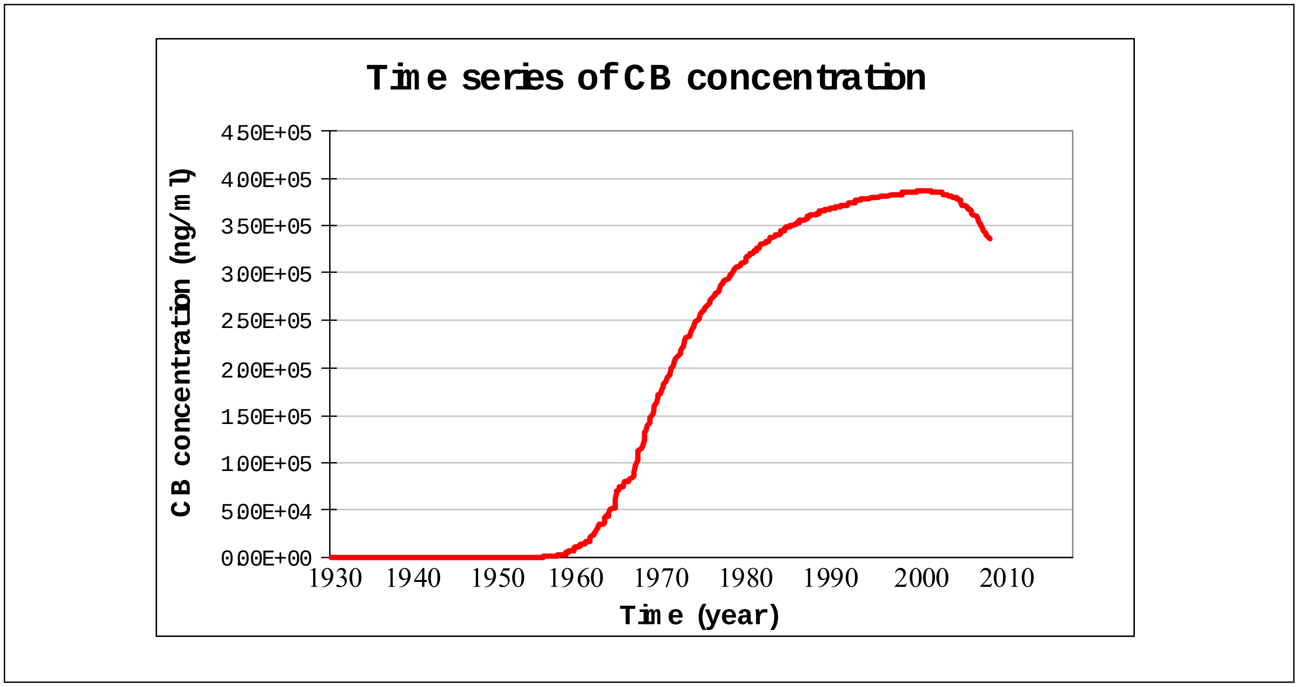

Figure 2. Time series of CB concentration obtained from 1D simulation.

degradation rate taking into consideration the limited availability of dissolved oxygen in the site. The CB concentration examined in the four monitoring wells showed that the microbially mediated degradation process under aerobic conditions was capable of removing CB of 11.7 mg/l on average, or only 0.08%. This amount of CB concentration was estimated to be degraded after 43 years of transport simulation using 45 years of half-life.

The development of the plume after 43 years from 1960 to 2003 as the result of transport simulation of the first scenario where the river is absent in the model domain is shown in Figure 4. However, the deviation between the plume after 43 years of transport and that within the shorter transport time is not distinct in Figure 4 as it exceeded the area of concern. It is important to note that the measured data utilized for calibration in this study was collected in 2003. Figure 5 shows the second scenario result of transport which was also performed for 43 years. A uniform CB concentration of 0.5 ng/ml is used for delineation of plume development as seen in Figures 3, 4 and 5. The comparison of those figures implies that the plume with the direction of pure groundwater flow without river interference is substantially more distributed than that when the river is present. Meanwhile the discrepancy of concentration under the first and second simulation scenario due to the presence of the river is examined at two observation wells (No.4 and 5) installed parallel to the river at distances of 130 and 300 m from suspected contaminant point sources. It is worth remarking that the average disparity of CB concentration of 8110 (50 %) and 7720 mg/l (70 %) seen as the loss of concentration in the model domain are observed at wells No.4 and 5, respectively as shown in Figure 6. It would seem that this amount of concentration is discharged to the river. Due to the fact that the velocity of the river flow is much greater by several orders of magnitude than that of groundwater flow, pollutant will spread at the contaminated site to a greater distance downstream. The plume development using a variety of concentrations after 43 years of simulation with the presence of the river is shown in Figure 7.

The simulation with pumping wells operating was carried out as the third scenario. In this simulation the pumping was assumed to start in 2001, which was two years earlier than that of the

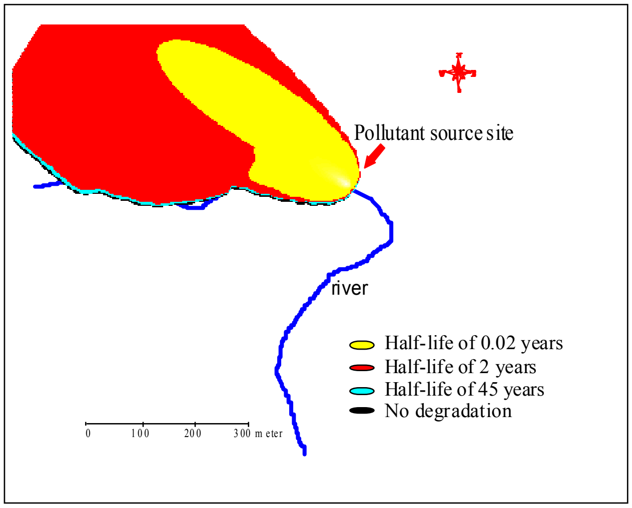

Figure 3. CB plume affected by various degradation rates for 43 years of transport.

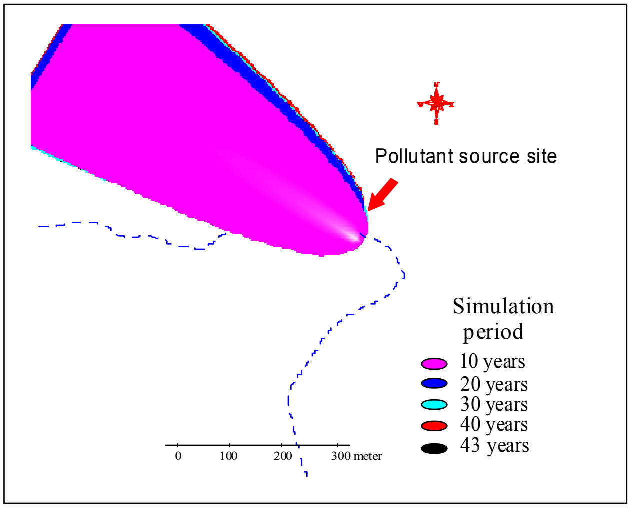

Figure 4. CB plume in the absence of river.

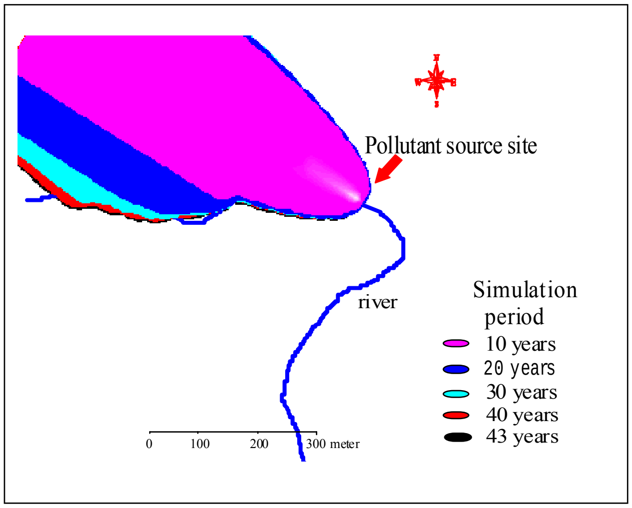

Figure 5. CB plume in the presence of river.

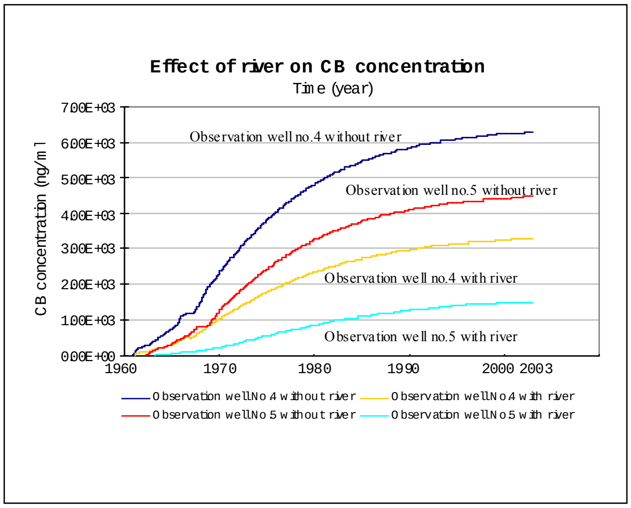

Figure 6. Effect of river on CB concentration at wells No.4 and 5.

sampling (2003). A combination of trials and analytical solution was used to examine the most reasonable magnitude of pumping rate. The result was operation of four pumping wells at a rate of 7 m^3/day each located parallel with the flow of the river at the central portion. Pumping wells No.1 and 2 are 80 and 5 m upstream of the pollutant source, respectively, whereas Nos. 3 and 4 are 20 and 105 m downstream of the source, respectively. The well location information is provided by the Fukuoka Prefectural Government. Figure 8 presents the groundwater flow map resulting from the third simulation scenario. The calibration of the simulated groundwater heads against the measured ones are in a good agreement as shown in Figures 9 and 10.

The analysis of pumping results obtained from the third simulation scenario indicates that pumping wells No. 2, 3 and 4 are able to reduce CB concentrations of 1840, 1380 and 581 mg/l, respectively, after 3 years of operation, starting in 2001 until 2003, while no concentration is appears in pumping well No.1. This is possibly due to the distance from the source being too large, and also the well location being unfavorable with respect to groundwater flow direction. The downstream location most influenced by pumping is observation well No.4, which is located 50 m away from the pumping well No.4 (or 130 m from the pollutant source). The different concentration between the second simulation and third simulation result as shown in Figure 11 reflects the effect of pumping on CB concentration.

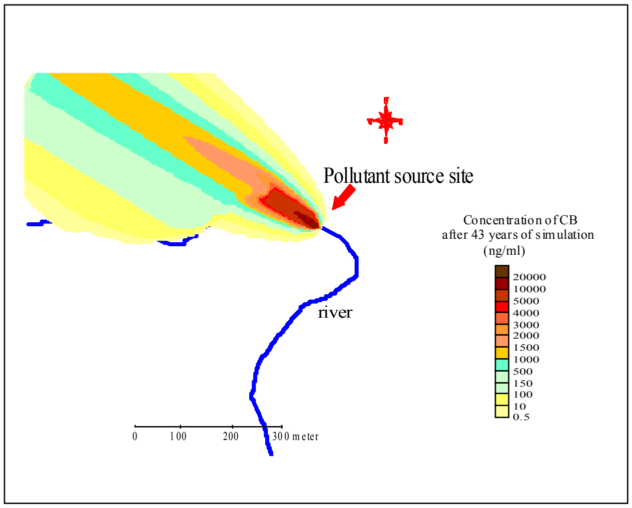

Figure 7. The development of plume after 43 years of simulation

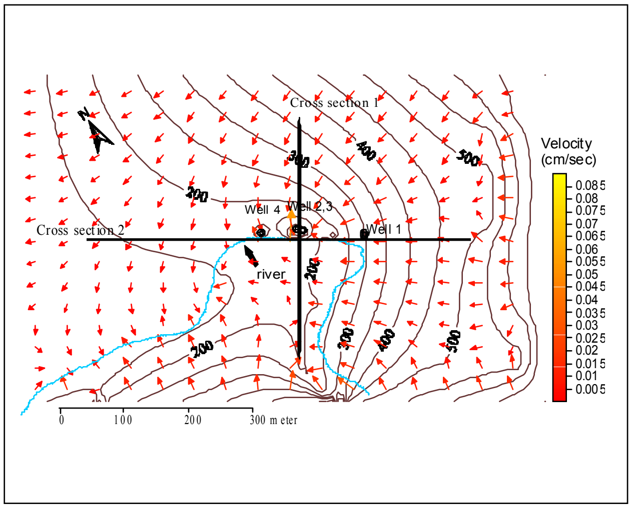

Figure 8. Map of groundwater head and flow direction

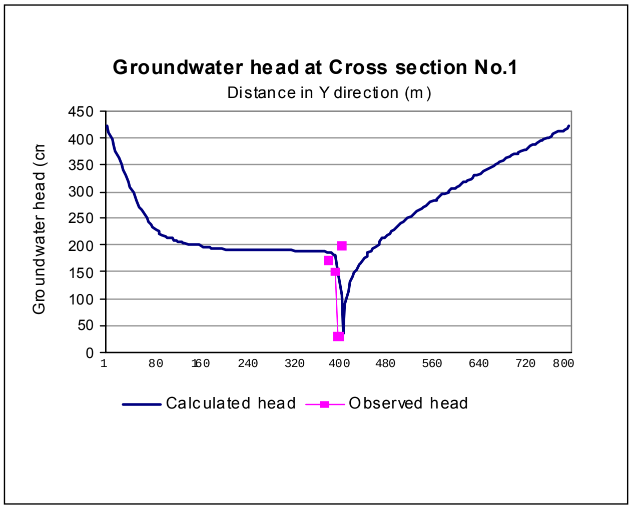

Figure 9. Comparison between the measured and calculated head

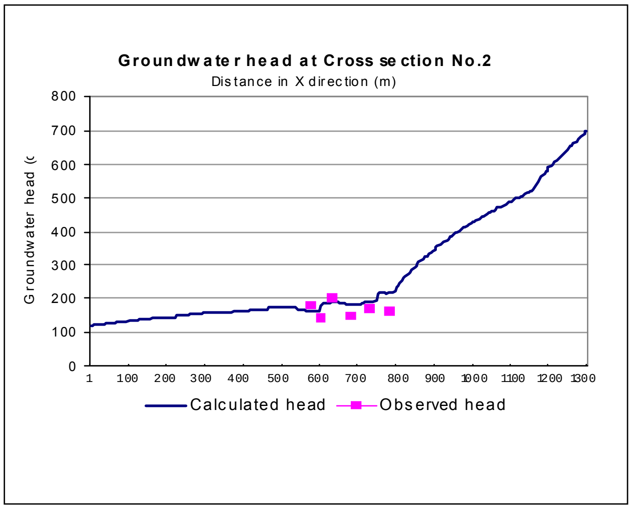

Figure 10. Comparison between the measured and calculated head

Since the simulation result under the third scenario is closer to the measured data than the two other scenarios, the assumption that the pump and treat type remediation scheme implemented in the contaminated site from 2001 is similar to this result is likely to be reasonable. It can also be stated that the predicted pumping rate, duration, and well position to some extent has functioned well on extracting 90 % of the CB concentration (3800 mg/l in total). This amount is obtained by comparing the concentration in 3 observation wells with and without pumping. Still, a considerable concentration of pollutants has been spread downstream, exposing a potential risk to people, the environment and business activities. It is of particular concern that the pollutants, through the river, may reach the sea, which regarded as a most vulnerable receptor in that area. Hence, appropriate monitoring and remediation work is encouraged to be conducted in the area corresponding to the predicted plume.

The predicted plume development after operating the pump and treat recovery system is shown in Figure 12. The illustration of plume extent constructed by the Fukuoka Prefectural Government according to the available measured data is shown in Figure 13. A comparison between Figure 12 and 13 indicates that the spreading pattern of the simulated plume is similar to that of the measured plume. Nevertheless, the calculated concentration plume was not able to be calibrated against the measured concentration due to the lack of observation data. By applying the three hypothetical scenarios, the effect of natural and man-induced processes on the contaminant spreading can be accounted for quantitatively. It may then be realistic to use the best scenario to project the extent of the plume in 2010 as shown in Figure 14. It can be seen that the estimated pumping rate, position and duration is capable of retarding further plume expansion in the future.

The dioxin limit standard in the aquatic environment stipulated by the Japan Ministry of Environment is 1000 pg TEQ which is equivalent to CB of 150 ng/ml consistent with the ratio between CB and dioxins in the site. Our previous 1-dimensional simulation showed that the mobilization of dioxins has been enhanced in the presence of CB. Therefore, the predicted CB plume may represent the plume of dioxins as well. It is also the basis for the use of the 150 ng/ml for CB contour delineation as in Figures 12 and 14.

CONCLUSION

The two-dimensional flow and transport model is designed in the present study to support the pathway analysis of chlorinated hydrocarbon pollution. The transport of CB carrying dioxins comprises the processes of advection, dispersion, adsorption and degradation. The proposed

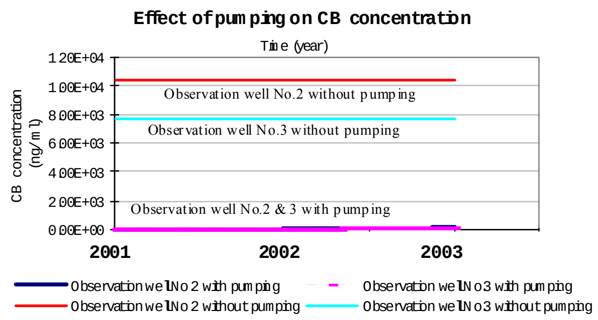

Figure 11. Effect of pumping on CB concentration at observation well No. 2 and 3

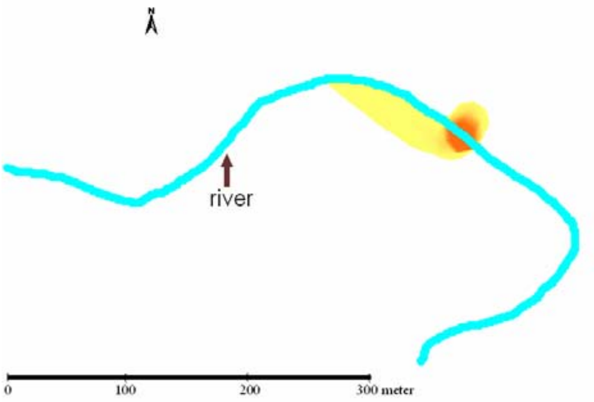

Figure 12. Predicted CB plume in 2003.

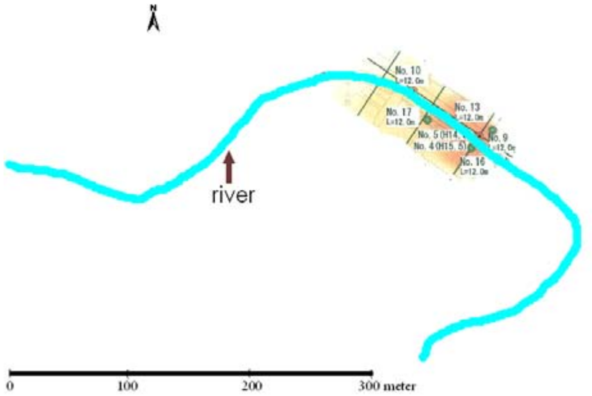

Figure 13. Observation data of CB plume in 2003.

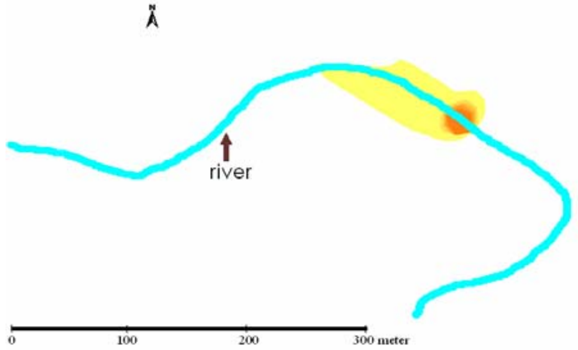

Figure 14. Projected plume extent in 2010.

modeling approach, employing various hypothetical scenarios, has demonstrated an ability to narrow down the uncertainty at the site and reveal the role of the various processes as they affect contaminant distributions.

The comparison between CB distribution in the absence of the river (the first scenario) and the presence of the river (the second scenario) examined in the two observation wells indicates that on average 50 and 70 % of concentration seeps to the river. This leads to contaminants spreading greater distances downstream along the river.

It was shown that the flow and transport of contaminants at the site have been affected by pumping (the third scenario). A hypothetical well pumping rate and duration were estimated by comparing the numerical solution with the measured piezometric head of groundwater. More than 90 % of the contaminant concentration observed in three wells was reduced after 3 years of operation at the four pumping wells during 2001 to 2003, suggesting that the high efficiency of multiple pumping techniques is expected to impede further migration of contaminants. In contrast, the plume already extends more than 130 m downstream of the contaminant source and cannot be captured by the current pumping configuration since the plume is beyond the pumping well capture zones. This portion of the aquifer should be considered for appropriate monitoring and remediation work in the future.

The results of simulation also show that the numerical approach is capable of recreating the natural processes (i.e. the presence and absence of a river) and man induced effects (pumping) on the distribution and behavior of the contaminant. It can be useful as a tool for reconstructing the history of release and estimating the future of the plume of contaminants, particularly where few data are available.

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