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Design of remediation of groundwater contamination by hazardous organic chemicals, Irkutsk region, Siberia

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Abstract This paper involves results of hydrogeological investigations conducted from 1990 to 1993 in Irkutsk region, Siberia, Russia. The main objective of study was groundwater contamination caused by hazardous chlorinated organic contaminants which percolate from liquid waste reservoir. Particular emphasis in this paper has been placed on practical approaches to solving contamination problems, development of protection and remediation measures and evaluation of their efficiency. This paper contains modelling results of an optimal drainage system that provided a complete interception of contaminated groundwater, and subsequent contaminant plume liquidation.

INTRODUCTION

Hydrogeological investigations and water sampling from monitoring wells have shown that widespread groundwater contamination caused by liquid wastes percolation from waste reservoir takes place at the study area. Mathematical simulation of groundwater flow and mass-transport has shown that in 12 (maximum 18) months contaminants would reach alluvial aquifer which is used for domestic water supply. Therefore, the necessity of urgent measures development for contaminated groundwater liquidation has arisen. The following describes investigations related to those measures.

SITE DESCRIPTION

The study area is located in Irkutsk region of east Siberia, Russia. A liquid waste reservoir is the main source of groundwater contamination within the study area (Fig. 1). The waste reservoir contains hazardous liquid wastes of some chemical enterprises. Initially, highly mineralized waste brines (with TDS concentration in 150-170 g l^{-1} and chloride ion concentration in 80-100 g l^{-1}, with density 1.2 g cm^{-3}) were disposed. Since 1986, liquid wastes of vinylchloride production have been disposed in that reservoir. These wastes are an emulsion (with density 1.35 g cm^{-3}) comprised chlorinated hydrocarbons: dichloroethane (62%), trichloroethane (25%), perchloroethylene (1.5%), tetrachloroethane (1.3%), chloroform (0.6%). They are accumulated at the bottom of the reservoir under the 2-m layer of waste brines. Preliminary balance evaluation has shown that the total loss of liquid wastes by percolation from the waste reservoir was about 10 m^3 day^{-1} (3 m^3 day^{-1} of brines, and 7 m^3 day^{-1} of organic contaminants).

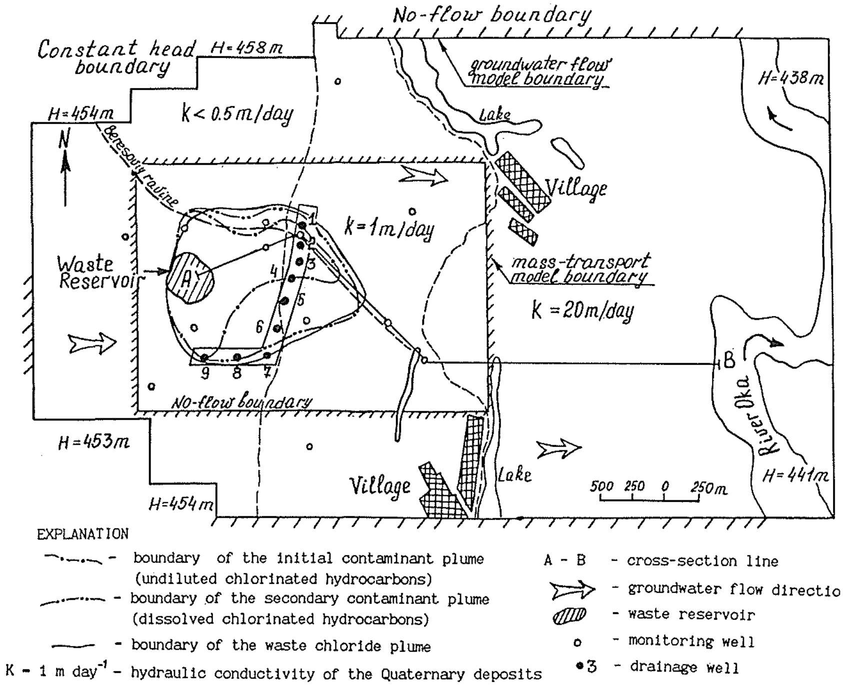

Fig. 1 Study area and some groundwater flow and mass-transport model features.

Groundwater occurs in two primary aquifers (Figs 1 and 2): the Quaternary aquifer (unconfined) and the Verkcholenskay aquifer (confined-unconfined). The background groundwater quality in the Quaternary aquifer is quite high. Concentration of TDS ranges from 300 to 400 mg l^{-1}, with primary ions calcium and bicarbonate. Concentration of chloride ions doesn't exceed 30 mg l^{-1}. This aquifer is widely used for domestic drinking purposes. The background groundwater quality in the Verkcholenskay aquifer is poor. Concentration of TDS reaches 3 g l^{-1}, with primary ions sulphate and calcium. The River Oka valley is the primary groundwater discharge area. Besides, groundwater of the Verkcholenskay aquifer discharges also into alluvial deposits and into some oxbow-lakes located within the River Oka flood plain as well.

IMPACT ON GROUNDWATER AND POSSIBLE PROTECTIVE MEASURES

An extensive plume of contaminated groundwater was formed at the study area by 1993. Contaminant transport mainly occurs within the Verkcholenskay aquifer. The boundaries of three contaminant plumes within this aquifer have been defined (Fig. 1). The initial contaminant plume was formed by dense liquid wastes percolated from the waste reservoir bottom. Due to that a vertical waste intrusion (body of undiluted chlorinated organic wastes) was formed beneath the waste reservoir (Fig. 2). The direction of undiluted dense wastes movement depends on direction and slope of the confining bed. The secondary contaminant plume is caused by partial dissolution of chlorinated hydrocarbons in groundwater and by the advective transport due to groundwater flow.

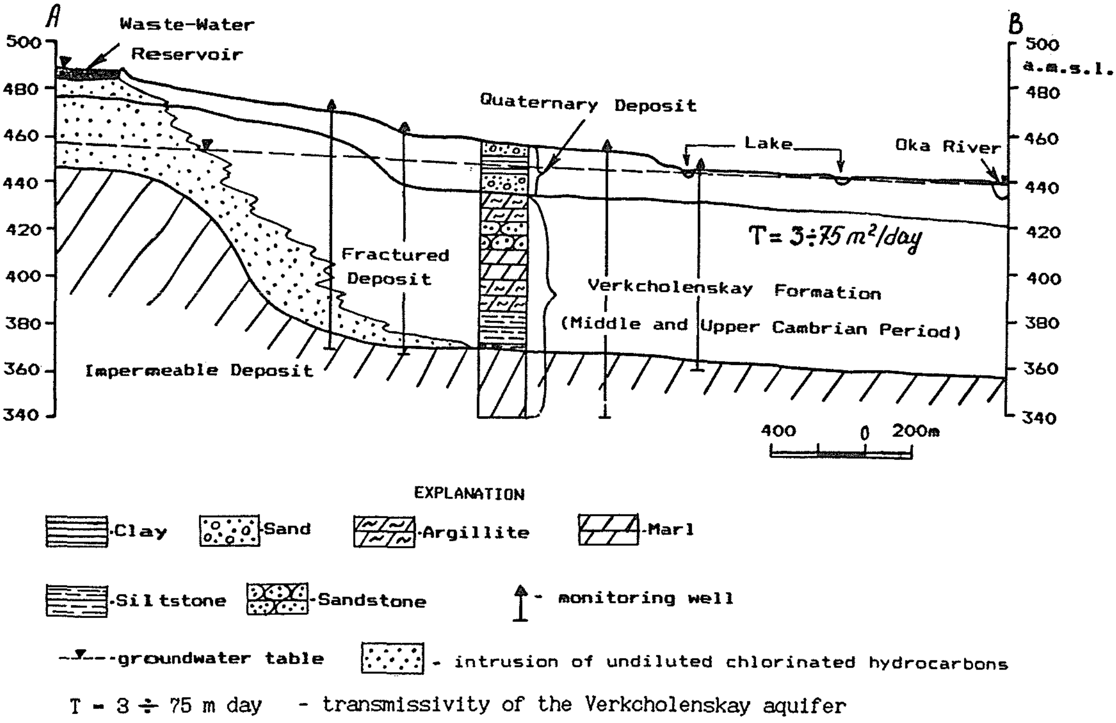

Fig. 2 Schematic hydrogeological cross-section of the study area.

The third plume is formed by chloride brines percolation from waste reservoir but concentration of chloride ion in groundwater even near the disposal site does not exceed 20 g l^{-1}, decreasing downgradient very rapidly because of intensive dilution by groundwater flow.

Groundwater contamination of the Quaternary aquifer has not been found up to now. But, as one can see further, there is direct risk for deterioration of groundwater quality of alluvial aquifer in the near future.

Groundwater protection measures were developed with special emphasize to dissolved chlorinated hydrocarbons, as these are most mobile and dangerous contaminants. As it can be seen from Fig. 1, the boundary of the dissolved chlorinated hydrocarbon plume coincides with the boundary of the waste chloride plume. It indicates that organic wastes are relatively non-reactive. This conclusion has allowed to study the behaviour of the plume of dissolved chlorinated hydrocarbons applying a simple advection-dispersion scheme of solute transport. Besides, the same protection measures will be suitable and effective for both dissolved chlorinated hydrocarbons and waste brines. After accurate analysis of all available geological and hydrogeological information, a pumping (drainage) of contaminated groundwater with its subsequent injection into the deeply laying cavernous limestones and dolomites was chosen as the first priority measure of groundwater protection at the study area. Hereafter, we will consider the problem of the drainage only.

GROUNDWATER FLOW AND DRAINAGE SYSTEM MODELLING

The design of the optimal drainage system was performed by application of numerical simulation methods. Two numerical computer models were build: groundwater flow model and mass-transport model.

Two-dimensional areal groundwater flow model (Fig. 1) was created using the program GEOWS (A. A. Roshal). It comprised the two hydraulically connected aquifers: the Quaternary aquifer and the Verkcholenskay aquifer. The waste reservoir itself and initial contaminant plume (undiluted hydrocarbons) were simulated as groundwater contamination sources. Using this model an analysis of hydrodynamical efficiency of different drainage system scenarios was carried out. The main requirements for choosing an optimal scenario were: (1) it had to provide the complete (100%) interception of contaminated groundwater; (2) total pumping rate of drainage water had not to exceed the maximum permissible injection rate (the potential capacity of the injection wells) which amounted 600 m^3 day^{-1}.

More than 20 different scenarios were simulated: number of drainage wells ranged from three to nine, with different well locations; duration of drainage system operation ranged from 30 to 3600 days. The results of such a multivariant modelling have shown that in the most wide scenario the drainage system has to consist of nine wells (Fig. 1), located near the front boundary of contaminant plume and divided into three lines. The first line of drainage system (wells 1, 2 and 3) has to be located within one local depression – the Beresoviy ravine, where transmissivity of the primary Verkcholenskay aquifer reached 75 m^2 day^{-1}. The second line includes wells 4, 5, 6 and the third one – wells 7, 8 and 9. As is shown in Fig. 3, groundwater flow inversion near the front boundary of the plume is entirely provided already after 30 days of just the first line of

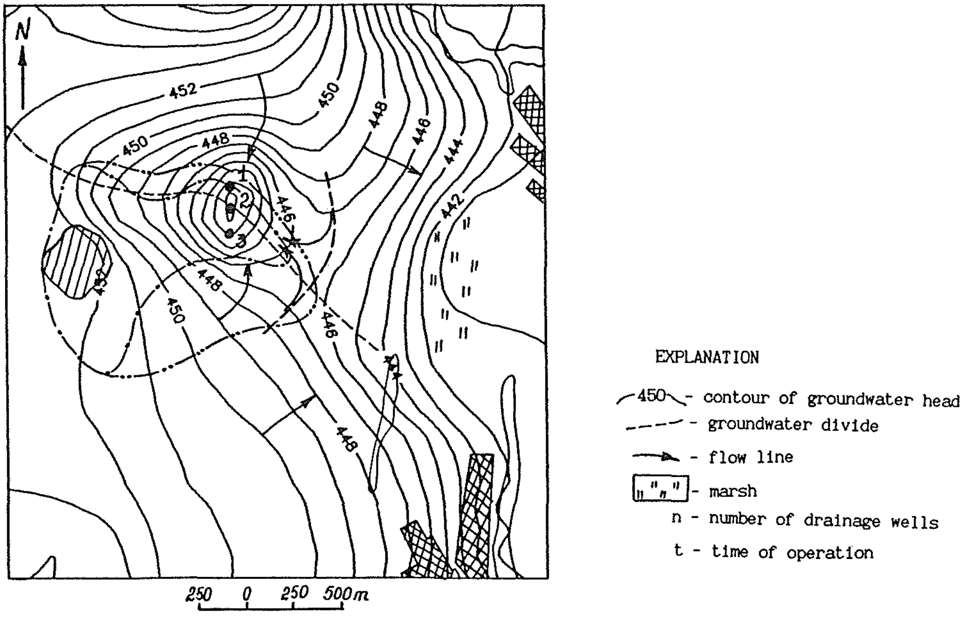

Fig. 3 Modelling results of the optimal drainage system operation (n = 3 wells, t = 30 days).

Table 1 Changes of pumping rate of drainage wells, from resulting groundwater flow modelling.

No drainage well line	No drainage well	Yield of drainage wells in m^3 day^{-1} (for four times steps)			
		30 days (1 month)	180 days (0.5 year)	1100 days (3 years)	3600 days (10 years)
I	1	200	140	122	117
	2	490	327	276	262
	3	111	72	59	56
	ΣQ_I	801	539	457	435
II	4	39	22	17	15
	5	45	28	22	20
	6	56	41	34	31
	ΣQ_{II}	140	91	73	66
III	7	57	44	36	33
	8	60	48	39	36
	9	64	51	42	39
	ΣQ_{III}	181	143	117	108
$\Sigma Q_{I+II+III}$		1122	773	647	609

drainage system exploitation and an artificial groundwater divide is formed separating the contaminated area from the River Oka flood plain.

The modelling results for all drainage wells are shown in the Table 1. The drainage wells were simulated in a regime of a constant water table drawdown which had to correspond to above mentioned total maximum permissible yield of drainage system. But as can be seen from Table 1, the total drainage rate exceeds the admissible rate (600 m^3 day^{-1}), even after 3 years operation of all three lines of the drainage system. It means that the practical recommendations have to provide a special regime of drainage system operation which would exclude the simultaneous operation of all three lines of wells.

CONTAMINANT TRANSPORT MODELLING

The mass-transport modelling was performed using the program M.O.C. (Konikow & Bredehoeft, 1978). Only the central part of the site was simulated (Fig. 1): from the waste reservoir to the nearest groundwater discharge area (oxbow-lakes). The contaminant transport model comprised only the Verkcholenskay aquifer. This is because the contaminant transport at the site takes place only in that aquifer.

The following input data were used: (1) the waste reservoir with constant contaminant loss by percolation was equal to 10 or to 0 m^3 day^{-1} (for the case when contamination source "is eliminated"); (2) drainage wells with "steady-state" pumping rates approximately corresponding to the rates at t = 1100 days (Table 1); (3) the concentration field for dissolved chlorinated hydrocarbons ranged from 5 g l^{-1} (near the waste reservoir) to 1 g l^{-1} (near the boundary of the contaminant plume).

Three main situations were consecutively examined:

(1) Natural conditions – the drainage does not exist yet. The modelling results are shown in Fig. 4. As can be seen from Fig. 4, the contamination plume will expand. Its boundaries will be more or less stable approximately in 2 years (745 days) when the contaminants reach the River Oka flood plain. For the initial time, t = 0, 1 June 1992 was taken.

(2) The first line of the drainage system is working. Contaminant percolation from the waste reservoir is going on. This situation is not demonstrated graphically in this paper. In this case, a stabilization of the plume boundaries takes place with some decrease of contaminant concentration within the plume. This containment of groundwater contamination doesn't solve the problem cardinally.

(3) The drainage system is working when the waste reservoir (as a source of contamination) is eliminated.

The results of the modelling enable to follow the changes of contaminant plume in time, from its decrease up to its disappearance. The results are demonstrated in Fig. 5. This is the case when the problem of groundwater contamination at the site can be fully solved.

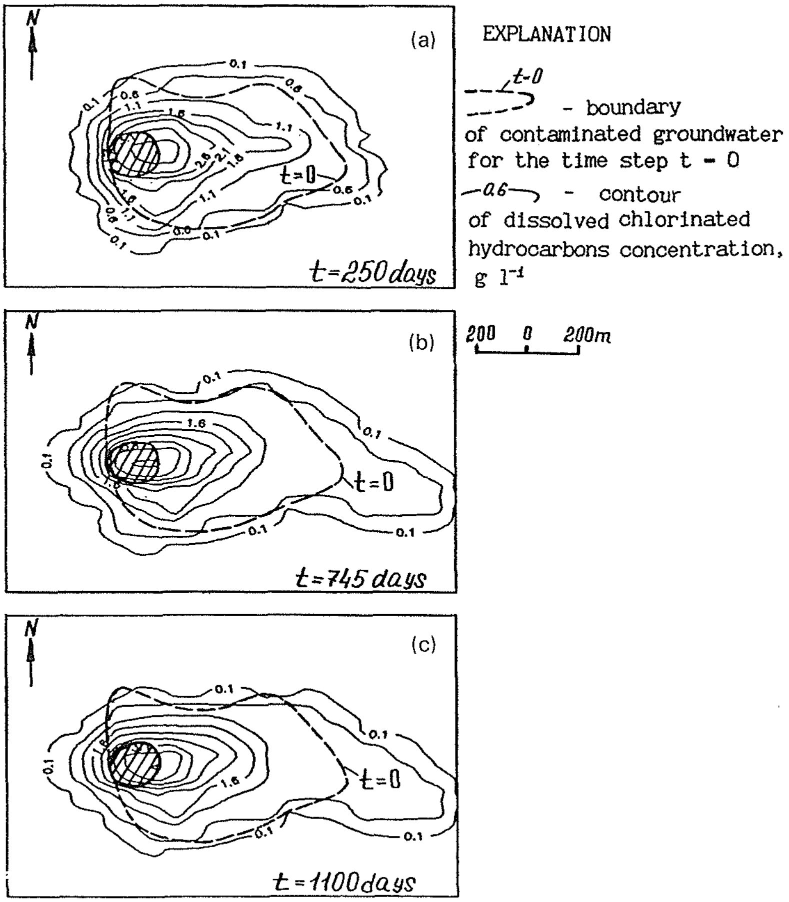

Fig. 4 Modelling results of groundwater contamination expanding when drainage of contaminants is absence: (a) t = 250 days; (b) t = 745 days; (c) t = 1100 days.

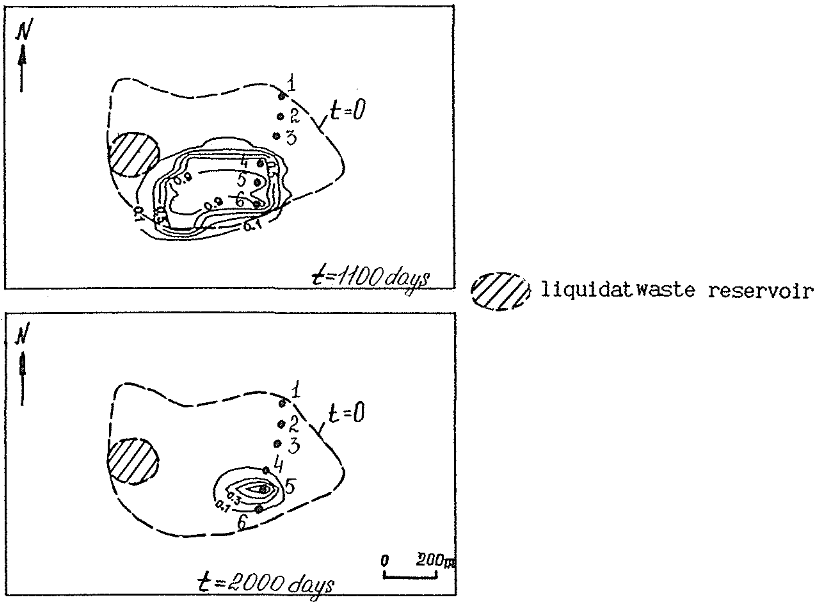

Fig. 5 Modelling results of groundwater quality restoration under the optimal drainage system operation (n = 6 wells) and when waste reservoir is liquidated: (a) t = 1100 days; (b) t = 2000 days.

CONCLUSION

Taking as a bases the above demonstrated numerical experiments, the authors have elaborated and recommended the following optimal alternative for liquidation of groundwater contamination in the examined conditions:

- First of all the source of contamination (waste reservoir) should be eliminated. As a minimum measure all the necessary activities should be done to stop the percolation of liquid wastes from the waste reservoir.
- Then the drainage wells of the first line (wells 1,2,3) have to be installed and put into operation – for using a high transmissivity of water-bearing rocks along the Beresoviy ravine.
- In the late third year of the first line drainage system exploitation the drainage wells 4, 5 and 6 of the second line should be prepared and put into operation. The first line of drainage system should be stopped.
- The drainage wells of the second line have to remain working up to the complete disappearance of the contaminant plume. It will take approximately 3 years more, so 6 years in total is the period of drainage system operation.

The authors would also like to emphasize the importance of combined application of the numerical groundwater flow and solute transport models, needed to solve a number of complicated problems like the one analysed in this paper.

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