A model of oil water disposal into heterogeneous aquifer

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ABSTRACT: In order to forecast injected oily brine spreading at P_2 aquifer, regional spatial filtration and migration models have been constructed. Trivial calculations shows that after 0.365 million m^3 of oily water is injected during 10 years, it will spread in the area with a diameter of only 250 m. Further spreading of oily water will be caused by the processes of advection of disposed brine, its dispersion, as well as sorption and biodestruction of hydrocarbons. Therefore the modelling shows that the brine spreading will be very slow - only after several thousand years the "tongues" of injected oily water can reach the Klaipëda waterworks situated at a distance over 20 km. However, admixture of brine in P_2 water will be in fact inconspicuous. Concentration of hydrocarbons even within the limits of oil fields will not exceed 0.3 mg/l.

1 INTRODUCTION

During operation of oilfields, a certain amount of oily water-brine is pumped out with oil. Lithuania's oil-fields are small, oil beds are not thick, and they are only partly filled by oil; therefore, in fact not only oil, but also oily water is extracted from all operation wells. Such water should be removed in some way.

Oilmen usually inject this water back into the oil bed, so killing two birds with one stone: environmentally hazardous wastes are got rid and the pressure is raised in the bed operated, i.e., oil is "pushed out" of the bed into the operating wells. However in Lithuania, to inject back the waste oil water into the wells is not so simple, since the oil-bearing bed occurs at nearly 2 km depths, moreover, the filtration qualities of oil- and water-bearing Cambrian sand and sandstone strata are not so good, therefore high pressure should be formed, in order to inject the water back into the bed, where it was taken from. For this purpose high-pressure compressors, pressure-resistant pipelines and other special and expensive equipment are necessary.

There is another idea how to solve this problem; it is used by Minijos Nafta LTD exploiting small oil-fields of Vilkyciai, Siupariai, Diegliai and Pociai, situated in the Minija River basin within the Gargzdai-Priekule-Sveksna triangular (Fig. 1). Already during prospecting of these oilfields it was noticed that oil water could be easily injected into shallower-lying Permian strata, instead of the Cambrian. The Permian is composed of fissured, cavernous limestone, therefore in some wells the borers found even catastrophic absorption of drilling mud into these strata. Moreover, Upper Permian strata water is mineralised and does not fit for drinking.

Having in mind the environmental approach, quite a few questions should be answered: * Is it possible that the injected oily water may enter overlying fresh water aquifers? * How far the oily water injected into P_2 aquifer can spread? * Will it reach fresh water zone ever? * Will the injection have negative impact on Klaipeda's waterworks Nos. 2 and 3 exploiting P_2 aquifer? * How high will be the disposed brine mineralisation? * How much hydrocarbons can be in the injected brine and how far can they migrate from the injection site?

All these questions should be answered after a detailed investigation of geological and/or hydrogeological conditions, constructing its filtration and migration models, and performing variation modelling.

2 GEOLOGY AND HYDROGEOLOGY

Upper Permian aquifer in West Lithuania is very well-explored since its fresh water zone is the main source of drinking water in the region. Significantly fewer investigations had been carried out in this horizon's mineralised water zone with its northern boundary going via Klaipeda and Gargzdai. Nevertheless there are numerous oil prospecting and geosurvey wells drilled in this zone. Only some of them, however, are explored a the P_2 aquifer. Moreover, there are also quite a few publications of general character dealing in detail also with issues of geological/hydrogeological conditions being under our interest (Perspectives… 1998).

So, P_2 aquifer in the above mentioned region occurs at 270-370 m depths going deeper from north-east south-westwards (see Fig. 1). The upper part of the section is composed of Quaternary deposits scanty in water, sporadic water-bearing Cretaceous and Jurassic deposits, whereas its lower part forms regional aquiclude composed of Lower Triassic clays reliably isolating P_2 aquifer from above – the fact is confirmed by many-year operation of Klaipëda water well fields (Juodkazis & Klimas 1991). So, the disposed brine cannot enter the fresh water zone in vertical direction.

Replies to other issues formulated in the introduction depend greatly on filtration and volumetric features of P_2 aquifer-forming rocks. They are limestone, dolomite, clay and gypsum. Their total thickens ranges in 40-80 m, but about as half of the rocks in the strata are water-bearing. Data of numerous regional studies show that in the area under description the P_2 horizon water-bearing rocks are very thick and their filtration qualities are very high only in a narrow tract, where after transgression of Zechsteinian sea contains algae bryozoan reefs (Geology... 1994). The reef formations are those which absorb drilling mud even catastrophically. The zones of full and catastrophic drilling mud absorption seem to be related to tectonic phenomena and karstification of P_2 deposits (Smilgys 1976). So these formations are very good for injecting brine.

We have already mentioned that there are few wells drilled in the mineralised water zone with P_2 aquifer tested. Most often only small inflows of water into the wells were observed; therefore it is impossible to speak about filtration qualities of the rocks in this aquifer only according to these inflow data. More informative data are obtained from drilling mud absorption in the oil-prospecting wells: there is no doubt the catastrophic and full absorption shows high filtration qualities of the rocks, whereas partial absorption or its absence show low filtration.

Some understanding about real values of P_2 horizon rock filtration parameters can be obtained from recharge models made and tested in this area (Juodkazis 1989). The models assume rock permeability parameter (T) reaches 3000 m^2/d in Klaipeda's well fields, 100-200 m^2/d south of Klaipeda, and about 10 m^2/d in the mineralised water zone. By combining all these and above-mentioned data, a scheme of P_2 aquifer filtration parameters has been made (Fig. 2). The areas of catastrophic drilling mud absorption are decided to correspond to the maximum filtration parameters seen in the freshwater zone, whereas full and partial absorption areas respectively correspond to the medium and lower than medium parameters. Moreover, maximum and medium parameter areas are thought to coincide with the spreading area of reefogenic formations. As determined according to laboratory analyses of cores, the porosity of these rocks is the highest, with average value making up 25%, whereas in the nearby areas it ranges within 6-12% (Smilgys 1976).

3 FLOW AND TRANSPORT MODELS

Before starting to solve any hydrogeological and/or hydrochemical problem it is useful to make a conceptual model, of descriptive character at least, and only later to compile more complex models reflecting the reality in the best way (Klimas 1996).

The issues formulated in the introduction should be replied by modelling. Solution of the problem about brine distribution in the P_2 aquifer mineralised water zone depends on the following: (1) quantity of brine to be disposed, its composition and disposing duration, (2) filtration/volumetric conditions of the accepting stratum, (3) groundwater flow gradient in the zone of unconditional water.

The quantity of the brine to be disposed looks like being more or less clear: now and in the future it will not exceed 100 m^3/d. Disposal duration is also known: it would not exceed time of licensed operation of the oil-fields, i.e. it would not exceed 10 years. So, about 365 000 m^3 of brine could be disposed in a decade.

Mineralisation of oil water from Cambrian strata to be disposed ranges from 108 to 168.9 g/l; for further calculations it is assumed to be 170 g/l. Specific weight of such water is 1.118 g/cm^3. We have already mentioned that the brine contains and will contain hydrocarbons. Of course, before disposal they will be separated in a special oil separator. The rest amount of hydrocarbons is 1 mg/l.

The scale of brine spreading in the unconditional water zone of P_2 aquifer can be preliminary valued according to simplified hydrodynamical schemes. For instance, real velocity of brine spreading is equal to:

$$U = kI/n_a \tag{1}$$

where k is filtration coefficient, m/d; I is groundwater flow gradient; and n_a is active porosity of rocks.

Radius of the area where brine is thought to be spread during the disposal time is:

$$R = (QT/\pi m n_a)^{1/2} \tag{2}$$

where Q is amount of brine to be disposed, m^3/d; T is transmissivity, m^2/d, m is thickness of the aquifer.

Transmissivity coefficient (T) is equal to 250 m^2/d in average, therefore at average thickness of the horizon of 50 m the filtration coefficient k = 5 m/d. Then let us assume porosity of rocks in the all area from oilfield to the Klaipeda unconditional water zone is equal to 0.2, and average groundwater flow gradient in the area between oilfields and Klaipeda is 0.001. Then it follows from (1) and (2) that

$U = 5x0.001/0.2 = 0.025$ m/d,
$R = (100x3650/3.14x50x0.2)^{1/2} = 107.8$ m

This means that the brine disposed would travel 2630 years (24 km) from Vilkyciai well V-2 to Klaipeda water well-fields, and nearly 3000 years from Diegliai well D-6 (27 km). In absence of groundwater flow and the disposal of 100 m^3 in 10 years, the brine would cover the area with a radius of only 107.8 m. After 10-year long disposal would be over, and the disposed brine in the unconditional water zone could spread and be distributed up to Klaipeda. The scale of this spreading will depend on hydrodynamical dispersion in the fissured rocks. Its basic characteristics are longitudinal and transversal parameters (a_L ir a_T) of the hydrodynamic dispersion (D) in the rocks.

Monitoring data for the Klaipeda water well-fields has shown that D parameter can be very high – from 8 to 12 m^2/d, hence, $a_L = D/U = 320\text{-}480$ m (Klimas, 1991):

$$\lg a_L = 0.5 \lg X \tag{3}$$

where X is migration distance (in our case – from oilfields to the Klaipeda water well-fields, i.e., 24-28 km).

So, $a_L = 280\text{-}380$ m. Standard ratio a_L/a_T is thought to be 10:1 (Fried, 1975).

After all necessary parameters were obtained, the filtration and migration models have been made. To compile filtration model software obtained from US company Environmental Simulations Inc. MODFLOWwin32 worked out for 3-D modelling water filtration processes and graphic interface GWVistas have been used (McDonald 1994; Polock 1994; GWVistas 1998). The size of the modelled area was approx. 3800 km^2 (68x56 km). At first this area was divided into 504 cells (blocks), from 4 to 16 km^2 in size (Fig. 2). Later, to make more details, the grid was made significantly more dense.

The northern and western boundaries of the plan model coincided with flow lines, therefore the 2nd type boundary condition Q = 0 is not realised in the model. At the southern and eastern boundaries the 2nd type boundary conditions is applied $Q = f(\Phi,x,y)$, i.e. groundwater flow entering the area modelled is given. The debit values are calculated from the former regional modelling results (Juodkazis 1989). Only one productive Upper Permian aquifer has been modelled, it was assumed to be reliably isolated both from above and below. So, within the vertical model boundaries, the 2nd type boundary condition is realised: Q = 0.

Stationary groundwater filtration corresponding to three pumping rate stages or operation periods in the Klaipeda water intakes Nos. 1 and 2 (Table 1). Exploitation of water well-fields in different periods is realised by defining constant water table in the well-field areas, i.e., the 1st type boundary condition H = f(t).

Table 1. Modelling of operation periods in the Klaipeda water intakes No. 1 and 2

Period	Well-field summarised pumping rate, thousand m^3/d	Water table in the well-field area, m NN
(1) 1960-1965	about 25-30	-15
(2) 1998-1999	about 30	-24
(3) 1983-1984	about 50-55	-36

Initial values of filtration coefficient k in the horizon for the model were determined according to the values of aquifer thickness (m) and transmissivity coefficient (T = km), then k = T/m. During model calibration these values were adjusted in order to get the better coincidence of modelled and real water table values in certain points (wells).

Calibration of filtration model is performed according to the arrangement of groundwater levels in 1960-1965; since during this period is most rich in factual information about the area modelled. Sum corrections of the model also have been made after the 1998-1999 period data. The modelled area is typical for groundwater of various mineralisation and specific weight, with different pressure values. Therefore mineralised water pressure values in the region were recalculated into freshwater pressure values, which later were used in all model hydrodynamic schemes. Depending on dissolved salt amount, real and recalculated levels differ from several centimetres to 4 metres.

The piezometric water table was restored in the model according to its state in 1960-1965. The difference between modelled and factual levels is small – it reaches 0.5-4.9 m in some points and does not exceed 3-5%. Rather good coincidence of the levels had been got in modelling the present hydrodynamical state. This enables us to use the calibrated model for solution of further problems: portraying hydrodynamic picture corresponding maximum pumping rate in Klaipeda water well-fields and modelling brine migration.

Forecast of the impact of brine burial in the model was done in two versions: (1) under present level of water-intake debit (about 30 thou m^3/d), when water table in the depression centre occurs at –24 m NN; and (2) at maximum water-intake debit (about 50 thou m^3/d) corresponding to groundwater safe yield approved by State Commission for Resources, when water table in the depression centre occurs at –36 m NN.

For each of the above versions, the situation has been modelled when injection of brine into V-2 and D-6 wells is done separately. For this purpose the model grid was detailed; its cells were made smaller to 125x125 m. Taking into account brine specific weight (1.118 g/cm^3), the quantity of water injected was relatively raised by 12%. So, the injection of 112 m^3/d of water into the strata was modelled to last 10 years.

It is quite understandable that such volume of water injected would not make any impact on hydrodynamic conditions in the stratum, since it is hundred times lower than the pumping rate of Klaipëda waterworks. According to the modelling results maximum rise of water table in the calculated model cells at the end of injection reached 1 m. However, it went down in the neighbouring cells up to the centimetres. As a result the piezometric water table remained practically unchanged in the area.

To make migration model the softwares MODPATH (Pollock 1994) and MT3D96 (MT3D96 1997) obtained from US Geological Survey have been used. The first one enables modelling migration of elementary water particles within the groundwater stream, and to evaluate pollutant migration direction and time. The second software is made to model migration of water-dissolved substances, including advection, hydrodynamic dispersion, destruction, sorption and other processes.

Additionally values of rock porosity, lengthwise and transversal dispersion indices and hydrocarbon destruction coefficient are to be given in the migration model. The following porosity values have been used in the models: 0.2 for Klaipeda water well-field and nearby fresh water zone, 0.25 in the reef zone, 0.12 in the region between Klaipeda water well-field and the reef, and 0.06 in the rest area.

Values of longitudinal and transversal dispersion (300 and 30 m. correspondingly) were given in the model according to the earlier made assessments for the Klaipeda water well-field. The value of water-dissolved hydrocarbon destruction coefficient in the model is given at 0.001 l/d. Several scenarios of disposed brine migration in the subsurface hydrosphere have been simulated by migration model.

4 DISCUSSION

Two basic brine disposal versions have been analysed: (1) into well V-2 in the Vilkyciai area; and (2) into well D-6 in the Diegliai area. It is assumed that 100 m^3/d of brine at 170 g/l concentration with up to 1 mg/l of hydrocarbons are to be disposed in a certain well for 10 years. Rate of brine dispersion, as mentioned above, will be caused not only by time-stable filtration and migration parameters but also time-depending groundwater flow gradient "*I*" changing due to operation (pumping rate) of Klaipeda wellfields Nos. 1 and 2 and specific boundary conditions in the aquifer (absolutely isolated limitless stratum). Although in fact Klaipeda waterworks Nos. 1 and 2 operate under conditions of non-stationary filtration, for simplicity, the filtration is assumed as stationary, moreover, two basic cases are simulated: (1) during the disposal period Klaipeda waterworks operate at a present-day pumping rate and form –24 m NN depression cone with corresponding water flow gradient; (2) maximum pumping rate of these waterworks is stable and equal to the approved safe yield (50,000 m^3/d), at a depth of depression cone of –36 m NN. These assumptions will not have any impact on forecasting, since real changes in the groundwater flow gradient, from filtration point of view, will be negligible in the highly permeable Klaipeda zone in all the cases.

Firstly, simplified spreading of brine is modelled according to so-called "piston push" scheme, where only elementary brine and unconditional P_2 aquifer water mixing and convective movement of filtration flow (advection) are taken into account. Moreover, for convenience, the mineralisation of unconditional water is assumed equal to zero, i.e., only concentration accrual caused by brine admixture is modelled. In another model case some hydrodynamical dispersion processes occurring in porous/fissured rocks and increasing dispersion of brine disposed and decreasing its concentration have been taken into account. Migration of small amount of hydrocarbons (up to 1 mg/l) in the P_2 aquifer unconditional water zone has also been simulated. Four migration cases have been analysed: (1) only mixing and convection (advection) processes taken into account; (2) the same with dispersion processes added; (3) only advection and hydrocarbon biodestruction processes taken into account in the model, and (4) advection, hydrodynamical dispersion and biodestruction processes taken into account.

First of all, changes in total dry residue of groundwater were modelled for the P_2 aquifer unconditional water zone with disposal of 170 g/l of brine into V-2 and D-6 wells. Modelling results are given in Fig. 3.

Modelling, as well as analytical calculations made at a conceptual level, showed that brine disposed during a 10-year period would spread in a small area and would not leave the square area with its side of 125 m. If dispersion processes are not taken into account, disposed brine concentration in both areas causes 85-percent increment of unconditional water concentration, whereas the dispersion processes are taken into account the increment reaches only 42.6%.

After 10 years, when the brine disposal is over, it spreads in the zone of unconditional water, and concentration of its mixture decreases. Therefore increment of unconditional water content also decreases. It decreases especially rapidly when hydrodynamic dispersion is taken into account. Fig 3 shows that, even after 1500 years, the spots of buried brine have not left the limits of licensed oilfield areas, and only after many many years they can approach freshwater zone and Klaipeda. However the increment of total dry residue of groundwater would be difficult to observe. Therefore, a conclusion has been made that disposed brine was to affect noticeably mineralisation of P_2 aquifer unconditional water only within the licensed area.

Several cases of forecasts made for distribution of small amounts of hydrocarbons (up to 1 mg/l) contained in brine to be disposed in the P_2 aquifer unconditional water zone are given in Table 2.

Table 2. Forecasts of spreading of modelled water-dissolved hydrocarbon maximum concentrations out of V-2 well in the P_2 aquifer – several cases

Time from brine disposal end, years	Water-dissolved hydrocarbon concentrations, mg/l							
	Operating Klaipeda wellfields at a present-day pumping rate				Operating Klaipeda wellfields at a maximum pumping rate			
	*	D	∝	D+∝	*	D	∝	D+∝
0	0.85	0.42	0.33	0.21	0.84	0.4	0.29	0.19
25	0.57	0.18	0	0	0.5	0.15	0	0
50	0.42	0.12	0	0	0.38	0.08	0	0
75	0.37	0.09	0	0	0.3	0.04	0	0
100	0.29	0.07	0	0	0.21	0.01	0	0

Note: * - only advection is taken into account in the model; D – advection and hydrodynamic dispersion processes taken into account; ∝ – advection and biodestruction processes taken into account; D + ∝ – advection, hydrodynamic dispersion and biodestruction processes taken into account

So, we can see that after 10 years of disposal of brine containing hydrocarbons at 1 mg/l concentrations, the content of hydrocarbons can decrease only to 0.84 mg/l level, if only their mixing in filtration flow with unconditional water (containing no hydrocarbons) is evaluated. However, if hydrodynamical dispersion and, especially, hydrocarbon biodestruction are taken into account, this amount will reach only 0.19-0.29 mg/l already at the end of disposal period; i.e., they will not exceed permissible levels for drinking water (0.3 mg/l). Further forecasts show that after 75-100 years this boundary will be reached in any case. Hence, oil in the mixture shall not exceed drinking water standards even within the limits of licensed areas.

5 CONCLUSIONS

The analysis of potential disposal of brine extracted together with oil in the licensed areas by Minijos Nafta Ltd in the P_2 aquifer unconditional water zone has been made. The results showed that hydrogeological conditions for planned disposal of brine with total dry residue reaching 170 g/l and containing 1 mg/l hydrocarbons in the Vilkyciai and Diegliai oilfield prospecting wells are highly favourable. P_2 aquifer in those sites contain mineralised water (about 8 g/l). The aquifer is safely isolated from the overlying aquifers by more than 150 m thick clay strata. The planned brine disposal site in P_2 aquifer shows occurrence of reefogenous rocks with their collector qualities being especially favourable for brine disposal: total thickness of these rocks in the reef exceeds 50 m, porosity reaches and even exceeds 25-30%. Before and beyond the reef P_2 rock thickness and porosity are significantly lower.

By using all the information available and compiling conceptual, filtration and migration models for brine disposal conditions, the potential consequences of such disposal have been analysed in a comprehensive way. It has been found that brine being disposed in a 10-year period would noticeably affect P_2 aquifer unconditional water mineralisation only in a zone with a radius of 125 m from the injection wells, whereas hydrocarbon content in the mixture would not exceed drinking water standard level. Later the disposed brine would disperse slowly – even after 1500 years, the "tongues" of injected oil water would not leave the licensed oilfield areas, and only after several thousand years they could reach town of Klaipeda, but brine admixture in P_2 water would practically be imperceptible. So, the brine disposed would not threaten Klaipeda wellfields.

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Gregorauskas M., Klimas A., Bendoraitis A. Modelis naftas ūdens glabāšanai neviendabīgā pazemes ūdens horizontā.
Nolūkā paredzēt naftas ūdens iesūknēšanas sekas P_2 ūdens horizontā ir izveidoti reģionālie telpiskie filtrācijas un migrācijas modeļi. Vienkārši aprēķini parāda, ka ja $0{,}365 \cdot 10^6 m^3$ naftas ūdens iesūknē desmit gadu laikā, tad tas izplūdīs laukumā, kura diametrs ir tikai 250m. Tālākā piesārņojošā naftas ūdens izplatīšanās notiks advekcijas, sorpcijas un ogļūdeņražu bioloģiskās noārdīšanās ietekmē. Modelēšana rāda, ka šis piesārņojums izplatīsies ļoti lēni - tikai pēc vairākiem tūkstošiem gadu tas var sasniegt Klaipēdas ūdens ieguves vietas, kuras atrodas aptuveni 20km attālumā. Taču piesārņojuma piejaukums P_2 ūdenī būs neievērojams. Oģļūdeņražu koncentrācija pat naftas ieguves vietās nepārsniegs 0,3mg/l.

Грегоравскас М., Климас А., Бендорайтис А. Модель хранения нефтяной воды в неоднородном водоносном горизонте
Созданы региональные пространственные модели фильтрации и миграции для прогнозирования последствий закачки нефтяной воды в водоносный P_2 горизонт. Простая оценка показывает, что закачка $0{,}365 \cdot 10^6 м^3$ нефтяной воды в течении десяти лет может распространится на площадь, диаметр которой будет только 250м. Дальнейшее распространение нефтяной воды как загрязнителя будет протекать под влиянием адвекции, сорпции и процессов биодеградации углеводородов. Моделирование показывает, что это загрязнение будет распространятся очень медленно - за несколько тысяч лет оно достигнет водозаборы Клайпеда, которые отдалены на около 20км. Однако загрязнение горизонта P_2 будет незначительным. Концентрация водоуглеродов даже в местах нефтедобычи не превысит 0,3мг/л.