

Assessment of fresh groundwater vulnerability to contamination caused by production operations in oil and gas fields of Nizhnevartovsk Region (Western Siberia)

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Abstract. Groundwater quality is possible to provide under the condition of aquifers effective protection from surface contamination and bottom pollution prevention in the areas of intense oil-gas production operations. Qualitative and quantitative assessment of groundwater vulnerability is based on regional characteristics of lithological composition and thickness of impermeable deposits in unsaturated zone and overlying deposits. The correlation of head and water table levels, absorption capacity of soils and clay rocks are also considered. An integrated approach to natural vulnerability analysis of groundwater has been presented. It suggests a combination of three most common methods. Based on performed calculations, the map has been made to plot fresh groundwater vulnerability of Atlym-Novomikhailovsk aquifer system (Nizhnevartovsk Region, Khanty-Mansiysk Autonomus Okrug).

1. Introduction

Assessment of natural groundwater vulnerability to contamination is a vital issue in hydrogeology. At present, the technogenic impact on groundwater can be seen most directly at regional scale. This problem is considered in the research with respect to natural vulnerability of aquifer system used for domestic water supply. Attenuation capacity has been assessed.

Groundwater vulnerability is defined as a degree to which main aquifer is being capped with low-permeable deposits capable to prevent surface contaminant seepage into groundwater. Groundwater vulnerability depends on many factors which fall into three groups: natural, technogenic and physico-chemical [1].

To prevent deterioration of fresh drinking groundwater quality and occurrence of new geochemical types due to anthropogenic impact, it is necessary to analyze natural vulnerability of groundwater in the study area.

2. Materials and methods

2.1. Study area

The target of the present research is groundwater of Atlym-Novomikhailovsk aquifer system composed of alternating sandy-clayey deposits which are 100 – 140 m thick. Water head varies from 108 to 154 m. Static groundwater level is at the depth of 2 – 8 m. The actual elevation ranges within



37.5 – 53 m. The overlying rocks contain Quaternary lacustrine-alluvial deposits. The water-saturated bottom section forms an aquifer. Groundwater occurs at the depth of 5 – 10 m. The thickness of Quaternary aquifer ranges within 22 – 28 m. This description has been made by authors of article on the basis of a hydrogeological section of Nizhnevartovsk Region [2].

There is a slight difference in groundwater table and head water level in Ob valley and its tributary basin, and it hardly exceeds two meters in watershed.

The deep-lying fossiliferous layer of permafrost has been traced. Sporadic permafrost occurs in the central part of the study area. Permafrost embraces sand and sandy-clayey deposits of Atlym and Novomikhailovsk suites. The depth to the top ranges within 60 - 105 m in watershed; while thickness varies from 45 to 100 m.

The unsaturated zone is composed of non-homogeneous layers containing different permeable, low-permeable and impermeable deposits which vary in composition and thickness. In flood-plain clayey deposits are hardly ever present.

In watershed, unsaturated zone and underlying Quaternary deposits are mainly clayey. Total thickness of sand and clay layers is defined by the ratio 2:1. Total thickness of overlying deposits is 40 - 70 m [3].

2.2. Sampling and analytical procedures

Based on the most frequent techniques, calculations of predicted time (T_1 , T_2 , T_3) of contaminant filtration from the surface to overlying bed of main aquifer have been performed. The basics of hydrodynamic calculations are described in standards [1, 4] and published literature [5, 6].

Apart from basic geological parameters (filtration coefficient, thickness of overlying rocks, porosity of water-resistant rocks), the first method considers difference in levels of groundwater and underlying bed.

$$\text{---}, (1)$$

where T_1 – the predicted filtration time calculated using the first method; $\Delta H = H_1 - H_2$ the head gradient, H_1 – the head of overlying bed; H_2 – the head of main aquifer; n – the porosity of water-resistant rocks; k – the weighted mean of filtration coefficient which is defined by the formula:

$$\text{---}, (2)$$

where m_i – the i -layer thickness, which overlies main aquifer; k_i – the i -layer filtration coefficient; k – the weighted mean of filtration coefficient.

The second method takes account of groundwater recharge rate and depth of groundwater runoff (h). In the study area groundwater recharge rate (M_e) is $4.02 \text{ dm}^3/\text{sec} \times \text{km}^2$ [7], consequently, depth of groundwater runoff is 126.774 mm/year or 0.127 m/year. With the reference to the given groundwater recharge rate, intensity of infiltration recharge (E) is 0.0003 m/day.

Contamination travel time is calculated by the formula:

$$\text{---} (3)$$

where T_2 – the predicted filtration time calculated using the second method; n_0 – the absolute porosity of overlying rocks (mean value 0.15), m_0 – the thickness of overlying rocks, k_0 – the coefficient of vertical filtration.

When using the third method, the intensity of infiltration recharge is the main parameter [5]. In this case the thickness of overlying deposits is indirectly considered:

$$\text{---}, (4)$$

where T_3 – the predicted filtration time calculated using the third method; W – the intensity of infiltration recharge at the groundwater surface. It accounts for 20 % of total precipitation, which, in its turn, makes 94 mm/year or 0.00026 m/day taking into account that average annual rainfall intensity is 471 mm/year; k_0 – coefficient of vertical filtration, which is defined as 1/20 average filtration coefficient in Quaternary deposits in watershed; μ – absolute porosity of rocks in Quaternary aquifer which is 0.1.

Based on the above-mentioned parameters, the time of vertical filtration through semipermeable deposits to domestic water producing aquifer was calculated, with each well tests considered individually.

3. Results and discussions

Time required for a contamination to migrate through overlying rocks to overlying bed of Atlym-Novomikhailovsk aquifer has been calculated using thirty well test series. Average values of contamination seepage time are given in table below according to data series from wells located along cross-sectional line.

Table. Results of average filtration time calculations in case of neutral pollutant (T average).

№ well	T ₁	T ₂	T ₃	T _{average}	Rank
551	13910	10714	12500	12375	4
N12-A,B,V	20376	12857	12000	15078	5
254	27670	15750	15750	19723	7
535	17158	12000	11200	13453	4
NZ-79	11178	10125	10800	10701	3
7-857	8003	8020	7952	7992	1
7729	8672	8571	8000	8414	2
7669	20840	12500	12500	15280	5
9 bN	13181	10500	9800	11160	3
27aN	9152	9750	10400	9767	2
6E	13766	10285	9600	11217	3
7-231	8862	9429	11000	9764	3
6	8939	8750	7000	8230	2
7166	8862	9500	11100	9821	2
Krp28	8862	9510	11150	9841	2
120e	8862	9440	11253	9852	2
7394	8862	9443	11000	9768	2
156	11178	11571	10800	11183	3
7675	21024	12900	12000	15308	5
nz-267	15649	12900	10900	13150	4
98-3	14955	11143	10400	12166	4
3	14955	11130	10500	12195	4
356	21024	15000	12200	16075	6
733	14955	11143	10400	12166	4
nz-230	25452	12900	12300	16884	6
nz-118	23954	14750	11800	16835	6
409	16875	13250	13250	14458	2
4k-3	20759	14250	14250	16420	6
429-3	14198	10928	12750	12625	4
383	10002	10071	9400	9824	2

Based on averaged calculated travel times of contaminants percolating unsaturated zone and Quaternary water-saturated deposits, the vulnerability map of Atlym-Novomikhailovsk aquifer system was made (figure 1).

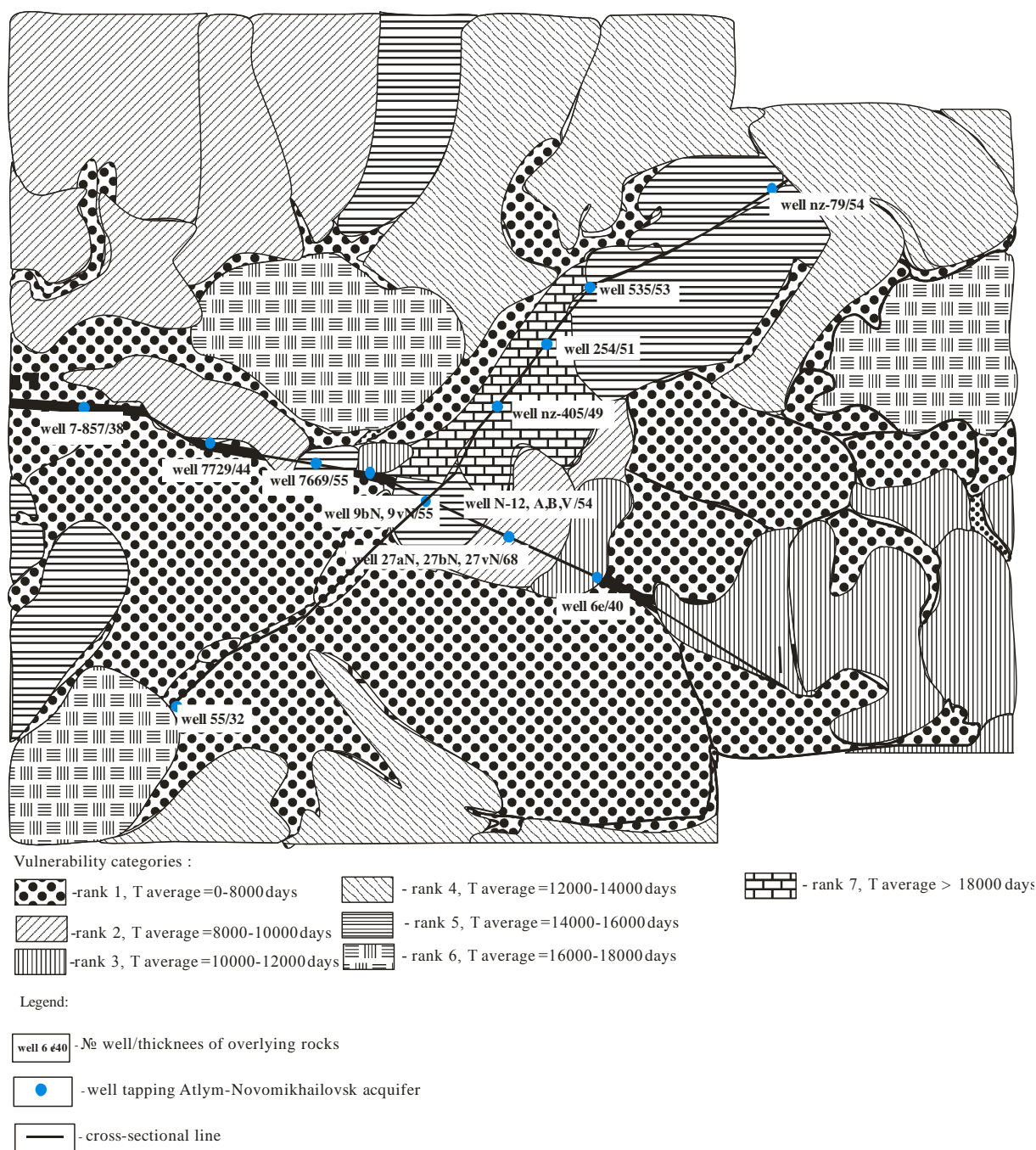


Figure. Natural vulnerability map of Atlym-Novomikhailovsk aquifer system (scale 1:500000).

It has been proposed to rate natural vulnerability of groundwater in Nizhnevartovsk oil-gas bearing area on 7-point scale: 1 - vulnerable, 2 – essentially vulnerable, 3 - weakly vulnerable, 4 – relatively invulnerable, 5 – sufficiently invulnerable, 6 – invulnerable, 7 – effectively invulnerable.

The scale takes account of estimated time for safe exploitation of an aquifer (before contamination due to vertical filtration), which, as a matter of actual practice, makes 25-50 years.

The most widespread are vulnerable groundwater (rank 1), with infiltration time being 0 – 8000 days. This estimate is a characteristic of boggy areas where highly sandy rocks are abundant in floodplains. Contamination travel time in these areas is 7992 days (well 7-857). Vulnerable groundwater occurs in

Ob valley and its tributary basin which are significantly deep. In these areas estimated time of safe groundwater exploitation is 22 years.

Boggy deposits are common in all geomorphological landscape types. Lithologically the deposits are composed of peats of different decomposition degree, clay loams, clay sands, with extensive inclusions of vegetable detritus and subordinate sand interbeds. Deposit thickness varies from 1.5 – 3 m to 4 – 5 m.

Talagaika suite deposits formed by alluvium laid down in Ob, Vaha, Vatinsk Egan paleo valleys are pervasive except for watershed zones. The sediments are fine-grained quartz sands interlayered with thin loams and clay sands. Graded bedding is observed in sands with gravel and pebble. Thickness of the deposits ranges within 8 – 22 m.

Essentially vulnerable groundwater (rank 2) is confined to the first terrace above the floodplain, which is located in the western and central parts of the study area. Though total thickness of overlying deposits is significant (35 – 68 m), clayey deposits are not more than 8 – 11 m thick which, in its turn, is not effective enough to protect groundwater from vertical contamination over the period of safe groundwater exploitation which is 25 years.

Channel facies composed of very-fine and fine-grained quartz sand is predominant formation in the cross-section. The upper layers are dust sands interlayered with subordinate loam and clay-sand; inclusions of vegetable detritus can be observed as well.

In the central and eastern parts of the study area there are local zones of weakly vulnerable groundwater (rank 3), which is assumed to be safe for exploitation over the period of 33 years. The thickness of low-permeable deposits is 12 – 14 m. The third terrace above the floodplain deposits are composed of fine-grained sands in the top and silts and silt clays – in the bottom. Based on different lithological composition, two deposit series have been distinguished in the cross-section of the second terrace above the floodplain. The bottom series is sand deposits while the upper – clayey deposits. The bottom series contains mainly sands and loams, whereas upper series contains silts, loam clays and clays.

The zones indicated as relatively invulnerable (rank 4) are mainly located along the watershed lines in the northern part of the study area. In these areas conventional contamination travel time increases to 14000 days, this is equal to safe exploitation time corresponding to 38 years. In these zones total thickness of overlying rocks is 54 m on average, with 15 m being composed of clayey deposits.

The zones of sufficiently invulnerable groundwater (rank 5) are less frequent, where groundwater is assumed to be safe over 44 years. These zones are observed in the central and eastern parts of the study area. They contain low-permeable deposits which are 20 m thick. This area mainly corresponds to deposits of second- and third terraces above the floodplain where the upper rock series is silts, loam clays and clays which function as barriers preventing migration of pollutants from the surface.

The zones of invulnerable groundwater (rank 6) which is safe for exploitation over 46 years are restricted to watershed lines and spatially correspond to areas of second- and third terraces above the floodplain. Low-permeable deposits differ in thickness from adjacent formations insignificantly.

The zones of effectively invulnerable groundwater (rank 7) are confined to permafrost which functions as a cryogenic acquiclude (northern part of the study area). In this case the aquifer is safe over the whole exploitation period.

Due to permafrost, clay-sand and loam deposits which occur in overlying beds, groundwater is least contaminated. However, indications of groundwater contamination, which is assumed to be irreversible, are obvious to the north of West-Siberian megabasin. This is due to the fact that groundwater contamination is directly proportional to technogenic impact and inversely proportional to its vulnerability. Under the conditions of areal distribution of potential contamination sources vulnerability analysis is the most vital issue.

4. Conclusion

Based on the analysis of concurrent calculation techniques, it has been indicated that according to the first method [1] maximum travel time is T_{average} (25452 days), whereas other methods to estimate this time [4, 5] yield a conservative value which is approximately 15750 days.

Thus, a substantial difference in quantitative estimates of groundwater vulnerability has been detected. When only one method being applied, assessment of groundwater vulnerability can be controversial.

More objective assessment of vulnerability can be provided when an integrated approach is being used. This methodology suggests using not only averaged values of safe exploitation times obtained as a result of concurrent analytical calculations but also methods of numerical modeling [9, 10, 11, 12, 13] taking into account rock sorption properties [8] when solving problems of geomigration forecasting.

Areal zoning of a particular oil-gas bearing area according to natural vulnerability enables to optimize location of observation stations which supplement the existing groundwater monitoring network in areas unprotected against contamination.

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