

RESEARCH ARTICLE

EVALUATION OF RESERVOIR PROPERTIES OF THE CENOMANIAN AQUIFER SYSTEM AT SITES OF PRODUCED WATER PUMPING AS EXEMPLIFIED BY THE WEST SALYM OILFIELD IN WEST SIBERIA

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ABSTRACT

The paper deals with one of the highly relevant problems arising from disposal of produced waters in West-Siberian oilfields. Produced waters are those co-recovered with oil. The water-cut factor (for oil) is well-known to reach 90% in West Siberia. This has led to widespread events for disposal of produced waters. Improving the procedures for prediction calculations of admissible quantity and quality of disposed waters is a topical problem in petroleum hydrogeology in West Siberia. This study reports a leak-off coefficient estimation for the Cenomanian deposits (the target ones for disposal of produced waters in most of oilfields across the region) of the Mesozoic hydrogeological basin. The calculation procedure widely used at present for a homogeneous confined aquifer does not reflect the true natural picture, as the aquifer into which the produced water is pumped is multilayered and heterogeneous. Here we look into natural processes for the formation of the West-Siberian megabasin, which have resulted in heterogeneous reservoirs: uncompensated sediment accumulation and present vertical fluid migration channels. Here we show that the gross thickness of the aquifer should be employed in leak-off and hydrodynamic estimations, and adduce the leak-off coefficient estimations for five oil wells in the West Salym oilfield based on the procedure suggested herein (factoring in the multilayered nature of the Cenomanian deposits). The average leak-off coefficient of sand streaks was 0.298 m/day, which we believe to reflect the natural condition of the aquifer more adequately than the standard estimation procedure used for a homogeneous confined aquifer.

KEYWORDS

stratalfissured waters, leak-off coefficient, test injections, groundwater pumping, West-Siberian megabasin, Aptian-Albian-Cenomanian aquifer system

1. INTRODUCTION

The disposal of produced waters in the West-Siberian oilfields has been a common practice for as many as a few decades. A huge amount of water that needs to be disposed of is co-recovered with oil. In general, this is mineralized water rich in Na and Cl ions. Wastewaters and residues resulting from hydrocarbon field development and operation are also subject to disposal. Discharging such waters into surface watercourses requires high-cost purification and preparation, therefore the disposal of underground waters into the Mesozoic reservoirs is an economically efficient and environment-friendly operation in most cases. The overall disposal technologies used in the region prove their worth. But their relevance to the disposal of produced waters into deep horizons remains controversial because the interior is polluted and there arises a risk of pollutants to infiltrate into the overlying water-bearing horizons (Beshentsev and Semenova, 2018).

The results of long-term observations of underground water quality in oilfields of the Khanty-Mansiysk and Yamalo-Nenets Autonomous Districts in West Siberia demonstrate that the composition of formation

waters remains relatively stable in terms of most of the recorded measures (Beshentsev and Semenova, 2018; Salnikova, 2021). This is achieved in many respects by strict adherence in oilfields to the guidelines regarding the chemical and bacterial compositions, temperature and quantity of impurities contained in injection waters (Industry Standard OST 39-225-88, 1990). The Cenomanian aquifer system related to the Mesozoic hydrogeological basin is widely utilized in the West-Siberian oil-and-gas fields to pump wastewaters. Figure 1 illustrates a typical constitution of the Aptian-Albian-Cenomanian aquifer system in the western Khanty-Mansiysk Autonomous District.

The Cenomanian lost-circulation horizon ($K_{1a}l_2+K_{2cm}$) within West Siberia represents clay streaks alternating with sandstone in most cases. One of the problems associated with disposal of produced waters into that system pertains to sediment leak-off coefficient estimation procedures. As per the paradigm commonly used in the region, all the prediction calculations are performed using the model of confined stratified aquifer (with its net thickness factored in), whereas the aquifer in which the produced water is pumped acts as a homogeneous fissured reservoir.

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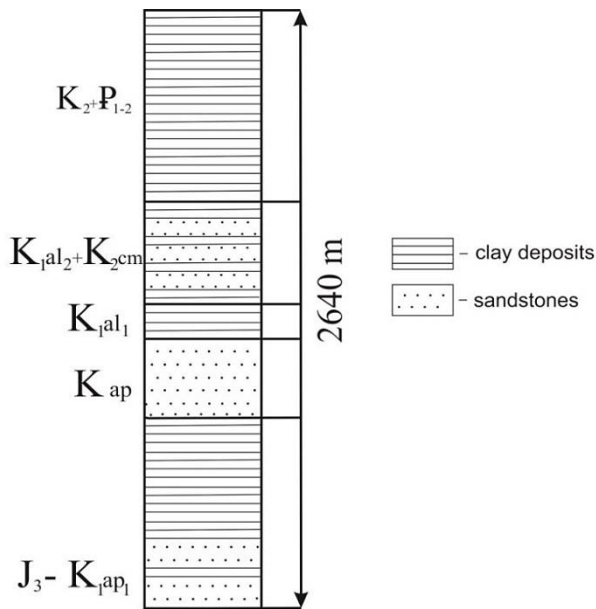


Figure 1: A typical architecture of the Aptian-Albian-Cenomanian aquifer system in the western Khanty-Mansiysk Autonomous District (built from Dyunin’s data (Dyunin and Korzun, 2005)

Because of the strata being multilayered and heterogeneous, the approach to estimating their leak-off parameters by the hydrodynamic and

geophysical techniques is ambiguous. The present study aimed to introduce a new estimation procedure for the leak-off coefficient of the Cenomanian deposits, which relies on the representation of a target horizon as being a fissured reservoir (a single unified hydrodynamic system) and which allows the leak-off coefficient to be estimated more precisely, we believe.

2. MATERIALS AND METHODS

2.1 The Causes Why Cenomanian Deposits are Heterogeneous

The high subsidence velocity of West Siberia has led to the unique-on-scale development of uncompensated sediment accumulation. The section of the sedimentary cover in the region is composed of the Jurassic-Cretaceous terrigenous formations which are dissected into terranes of sand-and-clay rocks (megacycles) identical in the structure and originated from the steady marine regression (Dyunin and Korzun, 2005; Abdrashitova, 2016; Nudner, 1970; Matusevich et al., 2005). The dissection into the terranes is due to the presence of transgressive clay sequences that have deposited in a cyclic manner. The regressive sequences (megacycles) were generated secondary to the non-uniform subsidence of the basin in its central and marginal parts when the sedimentary material was drifting constantly and chiefly from the East-Siberian platform and less from Ural and Kazakhstan. This contributed to some kind of a structure of the sedimentary strata that consist of wedge-shaped sediments that have accumulated from North to West or from West to East. The distribution of the sand and clay material within the wedge-shaped sediments follows a strict regularity. The megacyclit is divided into two portions: the subclay and subsand whose interface within the section has a slope and is “sliding” away from the bottom to the roof of the terranes in the direction from the drift area to the center of the basin (Figure 2).

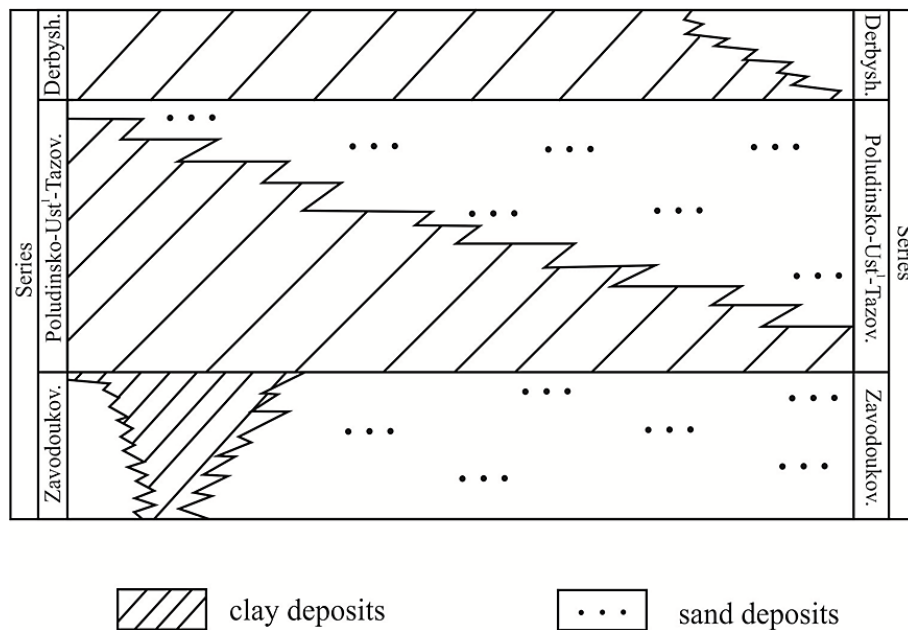


Figure 2: A schematic structure of the Mesozoic basin in West Siberia (Matusevich et al., 2005)

The megacyclits differ in the level of marine transgression preceded to their generation and in the volume of the incoming sand material. Three megacyclits can be differentiated in the West-Siberian megabasin section by the G&G data, each being associated with uncompensated sedimentation:

1. The Bolshekhetsky megacyclit (Zavodo-Ukovsky) (the Lower-Middle Jurassic);
2. The Poludensko-Ust-Tazovsky megacyclit (the Upper Jurassic to the Cenomanian);
3. The Derbyshevsky megacyclit (the Turonian to the Danian) (Matusevich et al., 2005).

The Cenomanian deposits refer to the Poludensko-Ust-Tazovsky megacyclit (the Upper Jurassic–Cenomanian). The formation of the megacyclit body was complicated by smaller-scale transgressions whereby polyregional clay strata were being generated. Therefore, all the said megacyclits can be categorized into smaller-priority cyclists but their structures retain the common structural features of a megacyclit. This is that reflected in the multilayered nature of the Cenomanian deposits.

Thus, the sedimentary cover of the West-Siberian basin that had formed under the uncompensated sedimentation conditions is composed of a series of fine, rhythmically embedded, wedge-shaped bodies which are united into larger-priority wedge shapes.

The binomial (oblique cross-section) distribution of the sand and clay material within the cyclits differing in priority predetermines the regular variation (the oblique one) in the hydrogeological closeness of the entire system and entails the difference in thermodynamic and geochemical velocities within the subclay and subsand subsystems for each sedimentation cycle and prevents the system from establishment of static and dynamic equilibria of the fluids. The delay of the thermodynamic and geochemical processes (relaxation) in the low permeability subclay environment of the cyclit, when compared to the subsand one, results in an inevitable increase in gradients of all types of hydrogeological features to the magnitudes that are ultimate (latching) for the two systems differing in thermobaric and geochemical behaviors to co-exist (Matusevich et al., 2005).

As a result, the subclay area of the cyclits undergoes a scattered mass-transfer transiting to the concentrated one whereby the hydrogeological

features are instable and highly stressed. In contrast, the scattered mass-transfer prevails in the subsandy areas of the cyclites to generate low-gradient hydrogeological features. Therefore, the leak-off coefficient estimations should factor in the multilayered nature and alternation of clay and sandy streaks; the presence of vertical fluid migration channels plays a part as well. A group researchers call these channels the "subvertical destruction zones" (Bembel et al., 2003). It is the subvertical destruction zones and the presence of small-amplitude dome-shaped and fault tectonic elements that probably cause fractured sheet reservoirs to form in terrigenous sediments, in addition to the elevated gradients of all the hydrogeological features. The leak-off coefficient estimation procedure taking account of the aforesaid insights on the structure of the Mesozoic basin in West Siberia is described hereinafter.

3. RESULTS AND DISCUSSION

The hydrodynamic methods (pumping, injection: single or cluster ones) imply the total testing of the strata (as homogeneous) and acquisition of an unambiguous (for homogeneous strata) and, at the same time, an averaged (for layered strata) parameter. The development target chosen for wastewater pumping may have a great gross thickness (over 850 m, for example, in the Yaro-Yakhinsk field located in the north-eastern Purovsky District, Yamalo-Nenets Autonomous Okrug in Tyumen Oblast) and a similar net thickness (over 500 m) and may exhibit a considerable leak-off heterogeneity. The thickness (gross) ranges from 23 to 177 m (average 134 m) for sandy layers, from 29.6 to 209 m (average 149.1 m) for aleuritic-sandy layers, and from 19.8 to 288.1 m (average 197 m) for aleuritic layers.

The aleuritic varieties can be viewed as relatively impervious layers. The basic operating ranges are considered to be sandy layers and, rarer, aleuritic-sandy layers (on pumping and injections). Perforation intervals are tried to be placed in these ranges. To determine the leak-off parameters of reservoirs under these conditions, it is reasonable to employ steady-state motion equations. Due to a sharp facies' variation, the sections even in neighboring wells are compared in broad lines only. Each permeable bed (interval) represents frequently interlayered, fine aleuritic-sandy (varieties) and clay streaks. The boundary resolution accuracy is 0.2 m. The least thickness of the delineated reservoirs is 0.4 m and the highest is 10–13 m. There are no clear lithological benchmarks within the area of the pumping site.

On the other hand, the reverse may be true for the Cenomanian reservoir oilfields (for instance, in the Upper Salym field located in Khanty-Mansi Autonomous Okrug): sandy and sandy-aleuritic streaks that determine the net thickness of reservoirs account for only 20–25% of the gross thickness (the gross thickness being 287.1 m and the net one being 69.3 m in the Uvat Suite—a development target as per G&G data). At the same time, the acquired Km values of 68.8 m²/day and 121.5 m²/day as per hydrodynamic surveys (a perforation length of 65.0 m (well no. 1B) and 78.5 m (well no. 3003B) should be referred to the gross thickness of the development target, while the type of reservoir waters should be referred to stratal fissured waters. Wells nos. 1B and 3003B are water wells.

Well no. 1B-Q=2260 m³/day, Km=68.8 m²/day;

Well no. 3003B-Q=1000 m³/day, Km=121.5 m²/day.

The conclusion that the Cenomanian head waters have stratal-fissure and fissure natures has to be made based on the common geological-hydrogeological conditions of their distribution area: a heavy Turonian-Eocene siliceous-argillaceous aquiclude of 600–700 m on the top (in the roof), quite heavy (20–40 m and higher) regionally persistent clay layers (formations of the Alymsk and Khanty-Mansiysk Suites) in the bottom, and a heavier (more than 900–1000 m) head coming from the roof of the Cenomanian aquifer system. The leak-off has an anisotropic nature in all directions with overflowing through local relatively impervious layers, and not only through pervious beds (the sandy and sandy-aleuritic ones). The leak-off area will look like an expanding sphere on injection and a collapsing sphere on pumping.

Under those conditions (stratal-fissured and fissure waters), it has no sense to delineate the net thickness, while leak-off and hydrodynamic estimations require using the gross thickness of the aquifer system. In that case, one should not refuse from geophysical well surveys that provide quite a detailed lithologic picture of the strata tapped with wells and enable their water transmissibility and piezo-conductivity to be assessed on the whole. It should also be borne in mind that the motion of filtration flows in the water-saturated strata (filtration areas) has a wave-like nature. To such conclusions has led the analysis of the structural and tectonic settings of oil-and-gas fields wherein small-amplitude dome-

shaped and fault tectonics is instrumental. So, this gives rise to consolidated granular sandstone reservoirs within tectonic fault zones. In accord with the Russian State Standard (GOST), the cemented sandy-clay rocks refer to semi-rocks with a uniaxial compression strength of 20–50 MPa, and chiefly fissured reservoirs and rarer the granular reservoirs may have formed in those rocks within crush and shear tectonic zones (Russian State Standard GOST No. 25100, 2020). An open cleavage fracturing is observed to be formed in the areas of positive dome structures, having vertical and diagonal directivities.

The hydrodynamic surveys more often use single tests in wells (pumping and injection trials and tests), while cluster pumping tests of observation wells (observation well testing) are rarer in use. The latter are the most meaningful, though complicated to arrange and costly. In the existing production settings, the subsoil user is very reluctant to perform cluster pumping tests at sites of wastewater injection and water intake. At the same time, single tests and monitoring observations at sites of injections and water intakes are being performed enough.

There arises a certain difficulty interpreting the results from such tests:

1. Identification of leak-off intervals in the perforated parts of the wellbores: the flow logging data in flowing wells are often absent for the reason of being lost, or such activities have not been completed.
2. Wellbore resistance measurement upon injection or pumping. The need to measure the resistance arises if using the steady-state motion equations (amended by Verigin and Shchurov and factoring in the penetration degree of water-bearing beds and the filter design (Maximov, 1967). It should be taken into account in this case that such a resistance is measured at the start period of the well operation (after the well has been constructed) or after the well workover because the resistance may considerably increase if the well is operating continuously.
3. Identification of the operating space of leak-off when the equations for unsteady filtration are used (the Theis-Jacob equations in order to interpret the tracing of pressure recovery and drop curves) (Maximov, 1967). Here we think, based on the aforesaid, that the leak-off area is the penetrated thickness of the Cenomanian aquifer system between the regional aquicludes**. It should also be noted that the tests with tracing the pressure recovery curve or pressure drop curve, after pumping or injection in single wells is stopped, provide highly understated results due to the borehole environment being muddied.

As the example of how to estimate the leak-off parameters of the Cenomanian aquifer system, we present their calculation for the pumping site in the West Salym oilfield. The input data for the calculations are given in Tables 1 and 2 and in Figures 1–5.

Well no.	Injection rate, m ³ /day	Pressure, atm
1359	332.64	35
1359	590.4	48
1359	832.32	60
1359	1152	71
32WW	216	35
32WW	331.2	48
32WW	547.2	60
32WW	806.4	70
38WW	115.2	35
38WW	165.6	48
38WW	252	60
38WW	388.8	70
40WW	165.6	35
40WW	260.6	48
40WW	417.6	60
40WW	421.9	70
41WW	417.6	33
41WW	718.6	48
41WW	930.2	60
41WW	1000.6	70

** The distance between the injection wells at the pumping sites is 0.5–2.0 km.

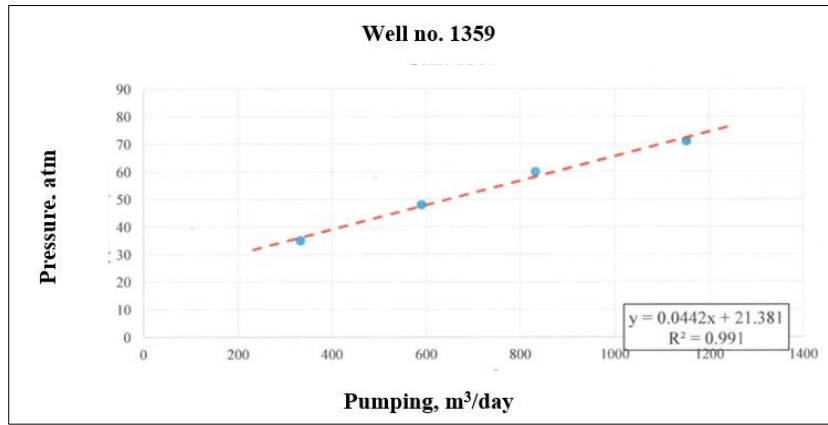


Figure 1: Processed testing data for injections in well no. 1359

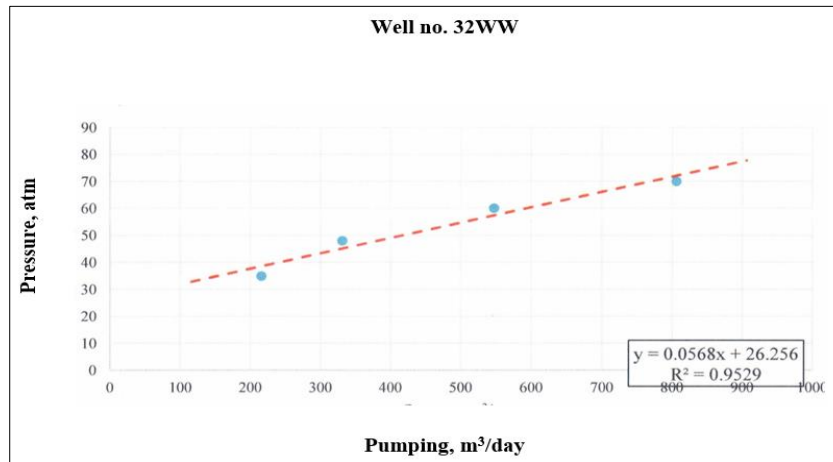


Figure 2: Processed test data for injections in well no. 32WW

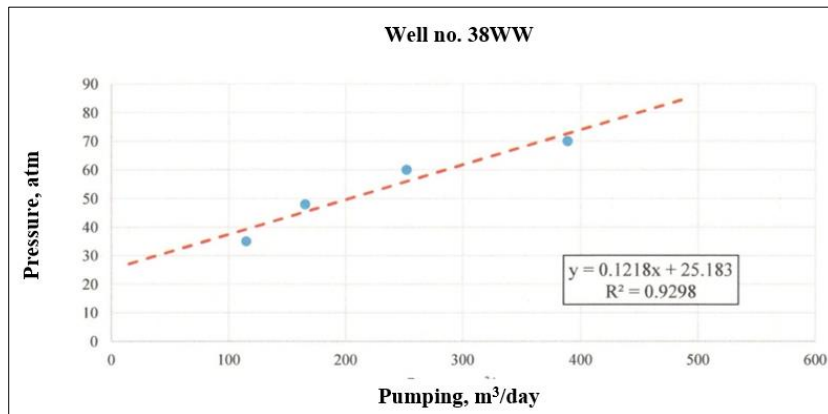


Figure 3: Processed test data for injections in well no. 38WW

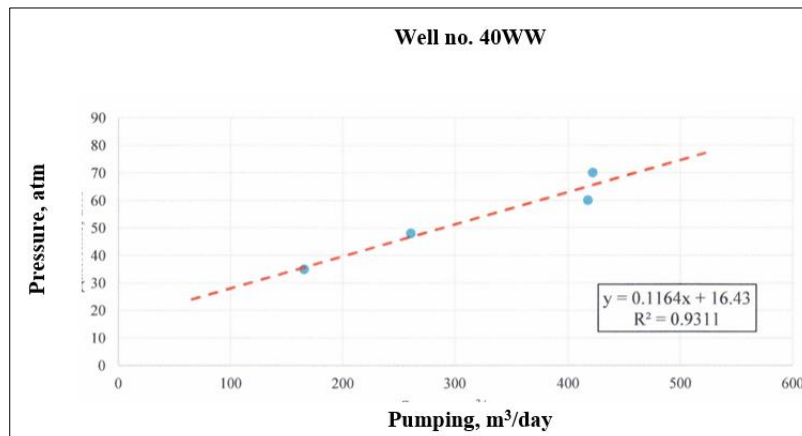


Figure 4: Processed test data for injections in well no. 40WW

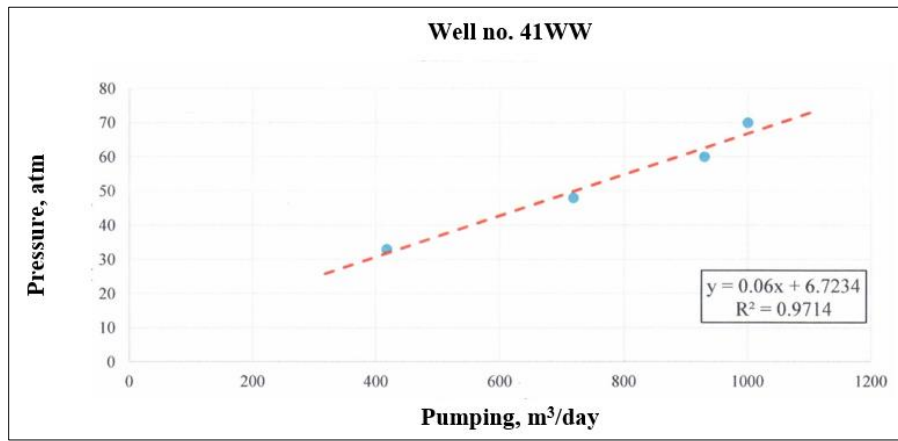


Figure 5: Processed test data for injections in well no. 41WW

To calculate the permeability coefficient (Cp) of rocks, we use testing data (for injections) and an equation derived from the Dupuit equation for the two-phase fluid (oil-gas) (Maximov, 1967; Bazlov et al., 1960; Bindeman et al., 1969).

$$Cp = \frac{K' \mu * (2.31g \frac{Rk}{r_e} + 0.5\xi_o + \xi_i)}{2\pi h e}$$

where Cp is the permeability coefficient, darcy;

μ is the dynamic viscosity of the fluid, cn;

Rk is the distance between the external reservoir boundary and the well, m;

r0 is the well radius, m;

he is the injection interval in the wellbore, cm;

K' is the well productivity index, cm³/s*atm;

ξi is the wellbore resistance as determined by the aquifer penetration degree;

ξo is the resistance as determined by the well design (filter);

Rk is determined by the observation well testing data at the sites of wells nos. 1359 and 1405, ~1500 m;

ξi is applied on the basis of Verigin's amendments by the $\frac{l_\phi}{m}$ (filter length l_ϕ to aquifer thickness m) and $\frac{r_0}{m}$ ratios (well radius to aquifer thickness) or by the equation given below (Verigin, 1962; Nikolaevsky, 1959).

he (lφ-fluid intake) is applied from the geophysical logging data (flow logging) by the well design.

ξi is estimated by Shchurov's equation:

$$\xi_i = \frac{425}{(L+1.5)N*d_o} - 0.6;$$

where, do is the diameter of the channel of openings, 0.8–1 cm;

N is the number of shots per meter;

L is the channel length, 16.5 cm

K' is the well productivity index as determined from the equation of a line that reflects the pressure stroke:

$$K' = \frac{Q_2 - Q_1}{P_2 - P_1} = \frac{1}{A'}$$

where Q1 and Q2 are injection rates at different stages, m³/day (cm³/s);

P1 and P2 are the injection pressures, atm;

A is the coefficient of the equation of a line for the fluid injection.

By using the relationship between K' and A, the following equation can be derived:

$$Cp = \frac{\mu}{2\pi * h e * A} * \left(\ln \frac{Rk}{r_e} + 0.5\xi_o + \xi_i \right)$$

The leak-off coefficient (Kφ) is estimated via the equation:

$$K\phi = 0.864 \frac{Cp}{\mu}$$

The water transmissibility is estimated from the value of the average gross thickness of the aquifer at the pumping site, 290 m:

$$K_m = K\phi * m_{cp};$$

Table 2: Input Data for The Estimation and The Estimation Results for Filtration Characteristics

Entry	well	Rk, m	r0, m	lφ, m, cm	μ, cn	0.5ξ0	ξi	A	Knp, Darcy	Kφ, m/day	Km, m/day²
1	1359	1500	0.089	4900	0.6	30.7	0.58	0.00382	0.209	0.301	87.29
2	32	1500	0.089	4000	0.6	38.3	-0.44	0.0049	0.231	0.3334	96.69
3	38	1500	0.089	1020	0.6	13.04	-0.44	0.0110523	1.24*	1.786*	518.0*
4	40	1500	0.089	3100	0.6	49.75	-0.44	0.010057	0.181	0.261	75.61
5	41	1500	0.089	2060	0.6	39.69	-0.44	0.00518	0.438	0.631	183.132
Average									0.265	0.382	110.63

* The result is exaggerated and excluded from the calculation of the average

The estimation input data and the estimation results for leak-off characteristics using the injection data for wells nos. 1359, 32, 38, 40 and 41 are summarized in Table 2.

The confined aquifer parameters are estimated by the equations for steady filtration using a solution to the problem of fluid influx to an imperfect well. The simple approximate solutions to such a problem were given (Babushkin, 1949). More accurate solutions based on the calculation models adopted by the cited authors were given derived more precise numerical values of the filtration resistance ξ within the zone of the sharp flow deformation nearby the imperfect well (Bindeman et al., 1969; Verigin, 1962).

The value of filtration resistance ξ0 for a single well upon both pumping and injection can be estimated by the equation:

$$\xi_0 = 2 \left(\frac{m}{l} - 1 \right) \left(\ln 1.47 = \frac{l}{r_e} - 2.65 \frac{l}{m} \right)$$

where m is the aquifer thickness, m; and l is the filter length of the imperfect well penetrating the aquifer, m.

This equation is applicable when $\frac{m}{r_e} \geq 100$ and $\frac{l}{m} \geq 0.1$. It warrants the estimation accuracy of ξ0 to an order of 8–10%.

The positive peculiarity of this method is that it is also applicable under unsteady motion conditions because the almost steady-state motion of underground waters nearby the test well is achieved relatively fast.

In our case, the equation applicability condition is met in testing wells nos. 1359, 32 and 40, and is quite close for well no. 41 ($\frac{l}{m} = 0.071$). For well

no. 38, the test gave an exaggerated result ($\frac{L}{m}=351$) by 2.5–2.8 times ($K_m \approx 185 \text{ m}^2/\text{day}$). Thus, the average of the leak-off coefficient for wells nos. 1359, 32, 40 and 41 is 0.382 m/day.

The estimation of the filtration intervals of the wells arouses some difficulty (Table 2). For instance, the general perforation interval in well no. 1359 is 49 m. The interval of 1286–1290 m (4 m) is a weak fluid-intake interval; 4 fluid-intake regions with a gross thickness of 15 m are observed from the flow logging in the interval of 1300–1332 m (32 m). Two fluid-intake intervals with a thickness of 6.2 m are observed in the interval of 1341–1354 m (13 m). The explicit fluid-intake intervals (21.2 m) reflect the actual leak-off velocity in the regions of enhanced fracturing or granulation (sands). The other regions should be viewed as being poor filtrating.

Wells no. 32, 38, 40 and 41 are water wells equipped for injection. These are equipped with mesh filters with installed well tubing strings in the upper perforation intervals (and higher), which chiefly operate (wells no. 38, 40 and 41). Besides, the leak-off inside the wellbore occurs in the upper intervals of the filters due to the pressure differential. A fluid intake was documented below the depth of 1576 m in well no. 32, presumably in the interval of 1595–1635 m (40 m) and was taken for the estimation. Given that the filtration mass permeability at the pumping site is quite inhomogeneous, one should have at least three points (wells) with sufficiently accurate tests for a more precise estimation. The said pertains also to the other alternative methods (observation well testing).

4. CONCLUSION

The findings from numerous studies on the structural and tectonic conditions of the West-Siberian oilfields demonstrate that the continuity of the Mesozoic hydrogeological basin is disturbed by the dome and fault tectonics; the sediments are multilayered and heterogeneous. This circumstance gives ground to gradually refuse from the commonly used estimation procedure for the leak-off coefficient of sediments by using the confined stratified aquifer model. Therefore, there is no need to delineate the net thickness, while the gross thickness of the aquifer system should be employed for hydrodynamic calculations. Here, the average leak-off coefficient of the Cenomanian deposits in the West Salym oilfield was estimated from the processed test injection data and constituted 0.382 m/day. In that case, it is recommended that the geophysical well logging data be used.

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