

Selection of filter parameters of Individual water supply systems

Vladimir Shcherbakov^{1,*}, Aleksandr Akulshin², Aleksandr Bachmetev¹, Anatolyi Akulshin²

¹Voronezh State Technical University, Moscow Avenue, 14, Voronezh, 394026, Russia

²Southwest State University, Kursk, ul. 50 let Oktyabrya, 305040, Russia

Abstract. The paper is devoted to the problem of optimal design, construction and operation of water supply systems and their elements. The key element of the system is a water well. The quality of its design and construction determines the operation of the water intake as a whole. Disadvantages in the construction of a well lead to disruption of the entire water supply system of a particular object. The paper proposed a methodology for selecting the optimal diameter and length of the well filter of a water well. Based on the methodology, an example of filter parameters selection for hydrogeological conditions of the city of Kursk is given. The above calculation showed that the use of the entrance velocity criterion in the design of wells can significantly reduce the cost of well construction while ensuring the design flow rate and allowable lowering of the water level. The cost of the filter, depending on the well design, is 20-30% of the total price for its construction. The most important filter parameters affecting the cost of a well are its length and diameter. Justifying the minimum diameter of the filter that ensures the designed water intake and allowable dewatering can significantly reduce the cost of the well, taking into account the fact that modern pumping equipment allows the use of columns of small diameter above the filter.

1 Introduction

Due to the growth of individual residential construction and the development of life-support communications, problems arise in the design and construction of water supply systems for small communities, individual residential and industrial facilities.

The most important element of the water supply system are water inlet structures, which determine the operational reliability of the entire system and its technical and economic indicators [1]. The widespread use of groundwater, which often does not require significant purification, is due not only to the environmental situation, but also to an economic factor [2]. Therefore, in solving common problems of drinking water supply from underground sources, an important role is played by the tasks of optimal design, construction and operation of water supply systems and their elements.

One of the most common problems of well operation on water is the clogging of the filter zone and the well filter. Repeated well washings give a temporary result. The

* Corresponding author: scher@vgasu.vrn.ru

productivity of the well gradually decreases with an increase in its resistance to the flow of water from the reservoir and, as a result, by clogging of the filter zone.

Based on this, there is a need to develop a special type of water wells, whose design, in terms of flow rate stability, is able to withstand the harmful effects of fine sand fractions contained in water, which leads not only to clogging of the filter and the filter zone of the well, but also to intensive abrasive wear of structural elements of a submersible pump [3].

Depending on the thickness of the aquifer or the depth of the underground flow, various types of water receiving devices are used. In Russia, for individual water supply, as a rule, dug wells and wells are used (Fig.1):

- with a small depth of the aquifer and its thickness, dug wells are used (Fig.1. a). Water from the well is pumped into the storage tank, from where by gravity flows to consumers;

- when the depth of the aquifer is more than 10 m and different thickness, wells are used. In (Fig.1. b), the scheme of individual water supply system with a hydraulic accumulator is presented. A downhole pump supplies water through a pressure pipe to a hydraulic accumulator equipped with an automation system. Water supply to consumers is carried out under forced pressure.

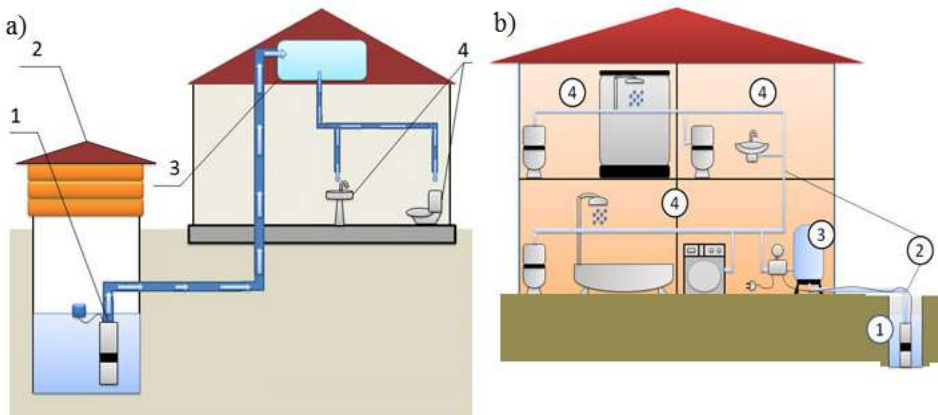


Fig. 1. Individual water supply systems: a) self-flowing: 1 –wellpump, 2 - well, 3 –storage tank, 4 – consumption points, b) withhydraulic accumulator: 1 –borehole pump, 2- standpipe, hydraulic accumulator and automation system, 4- water consumers.

For the use of water with the quality that corresponds to Sanitary Rules and Norms [4], individual consumers prefer to use water that lies deeper. That is why the deep well dewatering is widely used now. One of the main problems in the design of such systems is the selection of filter design.

The selection of a filter suitable for a specific geological condition of a well and ensuring a long operating time is a very difficult technical task. The geometric dimensions of the filter are determined by the filtration properties of the aquifer, the grain size distribution of the sands, and the technical conditions of the well operation [5]. Many of them are defined, such as the minimum internal diameter of the filter, the expected well productivity based on the experimental data, the level of decrease in the well.

The main and decisive indicator is the water-holding capacity of the filter and the permissible filtration rates. When calculating filters, it is necessary to determine their length, diameter, open ratio, and size of penetration openings. These filter parameters are determined in such a way that the input speeds do not exceed the allowable speed for the filter, i.e. $V_f \leq V_{allow}$.

The reliability of wells operation and the increase in the period between overhauls depend on the correct approach to the choice of the most rational way to obtain

groundwater, in particular, the design solutions of water wells. The development of new, promising designs of filter cages, the choice of shapes and sizes of inlet openings ensuring minimal hydraulic resistance and resistance to clogging is becoming increasingly important.

2 Materials and Methods

The most important filter parameters affecting the cost of a well are its length and diameter (Fig.2). Justifying the minimum diameter of the filter that ensures the designed water intake and allowable dewatering can significantly reduce the cost of the well, taking into account the fact that modern pumping equipment allows the use of columns of small diameters above the filter. Borehole pumps provide a wide range of capacities and water pressures with a small outer diameter.

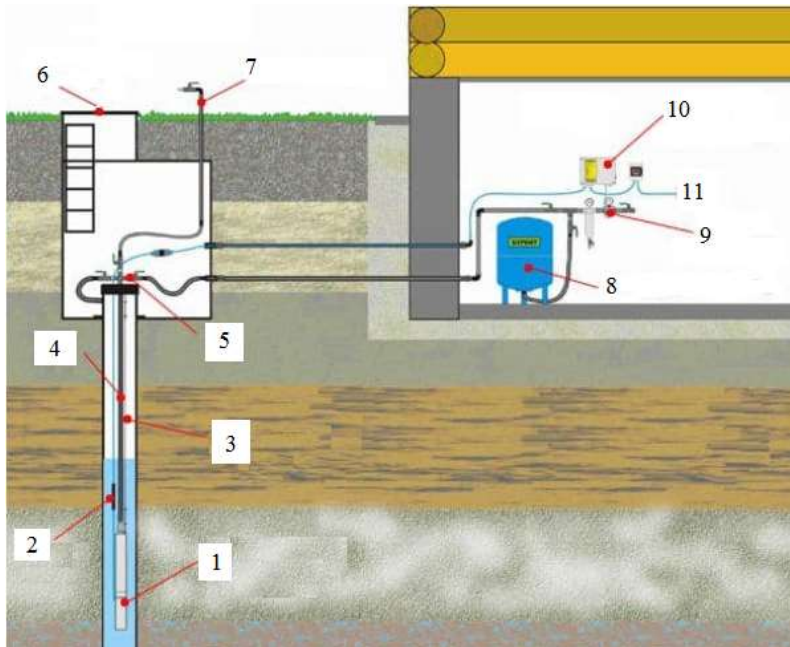


Fig. 2. Borehole water intake, where: 1- boreholepump, 2 – clutch, 3 - steel cable, 4- HDPPipe, 5 - sealed head, 6 - caisson, 7 - summer crane, 8 - membrane tank, 9 - pressure switch, 10 - control station, 11 - power supply.

To determine the filter diameter, the recommended criterion is the speed of the ascending flow in the upper section, which should not exceed 1.5–2 m/s. At the same time, an increase in the filter diameter does not lead to a proportional increase in productivity or a specific flow rate of the well [6].

The choice of filter length is important. Existing recommendations can be applied mainly to artesian aquifers. For unconfined aquifers, when calculating the filter length, the aquifer thickness should be reduced by half of the design decrease level.

3 Results

Analysis of well structures at many underground water intakes in unconfined aquifers suggests that in many cases, the filter length is 70–80% of the aquifer thickness, and the possible decrease in the level is insignificant. Over time, well productivity decreases due to

clogging of filters, which requires lowering the pump to the filter zone, which is unacceptable according to current standards [7, 8].

In foreign countries, there is a standard for wells in unconfined aquifers, according to which filters should be installed in the lower third of the aquifer [9]. This provides an adequate margin of reduction for the sake of the design flow rate and is consistent with the allowable decrease in the level of 2/3 of the aquifer thickness. In heterogeneous unconfined aquifers of great thickness, the principle of choosing the most penetrable interval applies only to the lower part of the section; however, in artesian aquifers, the location of such an interval does not matter.

When determining the optimal length of a water well filter, it is almost impractical to increase the filter length over 10 m for most hydrogeological conditions. This conclusion follows from taking into account the irregularity of the filter load along the length and is based on field studies at various water intakes [10]. For short filters (3–5 m), which should be installed, for example, in 10–15 m unconfined aquifers, this probability is not even discussed by Russian designers due to lack of application experience and justification methodology.

To substantiate the length and diameter of the water well filter, the criterion for the allowable rate of water entering the filter V_{entrance} (m/s) is used, which is determined from the expression:

$$V_{\text{entrance}} = \frac{Q}{F} = \frac{Q}{\pi D L_f \eta}, \quad (1)$$

Where F – area of filter openings, m^2 ; L_f – filter length, m ; D – diameter of the filter, m ; η – duty ratio of the filter.

The entrance velocity criterion is considered the most important tool for designing wells for water, which allows minimizing the cost of well construction while ensuring its high efficiency. The recommended entrance velocity is 0.03 m/s [11].

When designing wells, the standards of the American Water Works Association (AWWA) recommend to use entrance velocity from 0.03 to 0.46 m/s, given that the upper limit must be commensurate with the actual hydrogeological conditions and practice of design and construction of wells in a particular region.

When designing a well, it is required to successively determine: particle size analysis of samples of water-bearing rocks of the target aquifer, filter installation interval, type of gravel bedding, size of penetration openings, and filter diameter.

The dimensions of the filter penetration openings are selected depending on the particle size distribution of the contacting rock of the aquifer or gravel bedding. The maximum size of the filter penetration openings is taken from table 1. It should not be larger than the minimum diameter of gravel particles adjacent to the filter walls.

Table 1. The gradation of a gravel (or sand-and-gravel) filter pack material to specify the well screen slot sizes.

| | | | | | | | |
|---------------------------------------|------|------|-----|-----|------|------|------|
| Minimum grain diameter D_{min} , mm | 0.5 | 0.75 | 1.0 | 2.0 | 3.0 | 5.5 | 8.0 |
| Maximum grain diameter D_{max} , mm | 1.0 | 1.5 | 2.0 | 3.0 | 5.5 | 8.0 | 16.0 |
| Average grain diameter D_{50} , mm | 0.75 | 1.12 | 1.5 | 2.5 | 4.25 | 6.75 | 12 |
| Maximum size of filter openings, mm | 0.5 | 0.75 | 1.0 | 2.0 | 3.0 | 4.0 | 4.0 |

The entrance velocity criterion is applied when the filter length and duty cycle are known. Then, taking the minimum velocity of 0.03 m/s, the diameter of the filter can be determined by the formula:

$$D = \frac{Q}{F} = \frac{Q}{\pi V_{entrance} L_f \eta}, \quad (2)$$

The final decision must be made taking into account the real hydrogeological conditions, given that reducing the filter length leads to an increase in the imperfection of the well according to the degree of opening, i.e. an additional decrease in the level.

In addition, it is known that water, coming up to the filtering surface, is pressed in its openings and, with increased speed, streams out of the grate into the filter by separate water threads. Thus, there are losses associated with both the entrance to the openings and the sudden expansion at the exit of the filtering surface opening into the internal chamber of the filter (Fig. 3).

The total hydraulic resistance of any network element is determined by the formula [5,12].

$$\Delta p = \xi \frac{\rho \omega_1^2}{2} = \xi \frac{\rho}{2} \left(\frac{Q}{F} \right)^2 \quad (3)$$

Where Δp –loss of total pressure, Pa; ξ –hydraulic resistance coefficient; ρ –fluid density, kg / m³; ω_1 –flow rate, m/s; Q –volumetric flow rate, m³/s; F –total area of filtration openings, m².

The total losses in the filtering surface made of wire of various cross-sectional shapes consist of the losses due to entrance, friction, and sudden expansion (impact) at the exit of the narrowed section between the wire into the filter chamber.

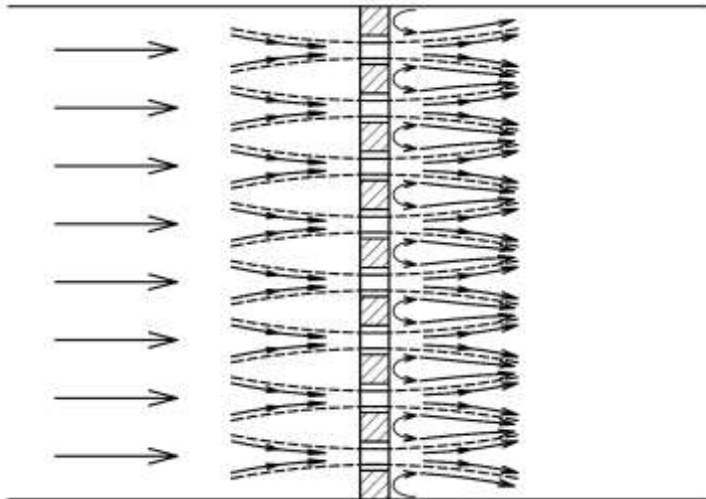


Fig. 3. Flow pattern (flow) of water flow through the filter surface.

Some forms of wire section and their parameters are shown in Fig.4.

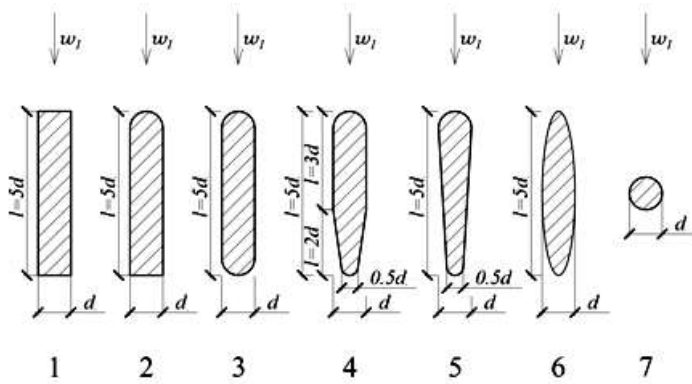


Fig. 4. Filtration wire section shapes, where: 1 - rectangular; 2 - rectangular rounded on one side; 3 - semicircular with straight inserts; 4 - semicircular elongated on one side; 5 - drop-shaped; 6 - elliptic; 7 – round.

The resistance coefficient of the gratings with $l/d_m = 5$ and $d_0/S_1 \geq 0.5$ can be determined by the Kirschmer equation [12]

$$\zeta = \frac{\Delta p}{\frac{\rho w_1^2}{2}} = \beta_1 k_1 \sin \theta. \quad (4)$$

Where β_1 - rod shape factor (Table 2,3); $k_1 = \left(\frac{S_1}{d_0} - 1\right)^{4/3}$; θ – the inclination angle of the wire to flow, d_m – width (diameter) of midsection of filtration wire, m; d_0 - distance between two adjacent turns of wire, m; S_1 – the distance between the axes of two adjacent turns of wire, m; l - the length of the cross section of the filtration wire, m.

Table 2. Values of coefficient β_1 for different forms of rods.

| No of rod | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|-----------|------|------|------|------|------|------|------|
| β_1 | 2,34 | 1,77 | 1,77 | 1,00 | 0,87 | 0,71 | 1,73 |

Table 3. Dependency values $k_1 = f\left(\frac{d_0}{S_1}\right)$

| $\frac{d_0}{S_1}$ | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|-------------------|----------|------|------|------|------|------|------|------|------|------|-----|
| k_1 | ∞ | 18.7 | 6.35 | 3.09 | 1.72 | 1.00 | 0.58 | 0.32 | 0.16 | 0.05 | 0 |

It follows from the formula (1) that the volume flow rate of filtered water is equal to:

$$Q = F \sqrt{\frac{2\Delta p}{\xi \rho}} = F \sqrt{\frac{2\Delta p}{\beta_1 k_1 \sin \theta \rho}}$$

It follows that water consumption is inversely related to hydraulic resistance. Therefore, the greater the value of hydraulic resistance, the lower the performance of the filter.

4 Discussions

Consider an example of the selection of the length and diameter of the filter for the hydrogeological conditions of the city of Kursk. Currently, in the Kursk region, the largest intake of groundwater is in the Alb-Cenomanian aquifer - about 61%. This aquifer is distributed everywhere, except for the territories confined to the river valleys, where its deposits are washed out. In most of the region, it is the first from the surface. It is accepted that the aquifer represents itself as a single Quaternary-Cenomanian-Aptian complex connected hydraulically [13].

Quaternary deposits represented by fine-grained sands are significantly inferior in their filtration properties to the underlying sands K1+2al+cm of the Cenomanian aquifer. Considering that when operating water wells, the dynamic level at the water intake will be close to the bottom - that part of the aquifer, and in water wells it will be even lower, then when choosing the place of installation of filters, it is advisable to consider operational the Cenomanian sand deposition aquifer fed by both the upper Quaternary sands and the lower Aptis sands. The thickness of this layer is about 15 m.

According to the principles adopted in theory and practice, this aquifer when constructing wells for water should be equipped with a filter in the lower part within 2/3 of its thickness, which is approximately 10 m [14].

On the other hand, the geometric dimensions of the filter are determined by the filtration properties of the aquifer, the particle size distribution of the sands, and the technical conditions of the well operation [14]. Many of them are defined, such as the minimum internal diameter of the filter, the expected well productivity based on the experimental data, the level of decrease in the well. Consequently, the main and decisive indicators are the waterholding capacity of the filter and the permissible filtration rates.

The water holding capacity of the filter is determined as follows:

$$Q = FV_{entrance},$$

Where $F = \pi D l_f$,

Q – water well flow rate, m³/day. (m³/h); F - filter area, m²; D - filter diameter, mm; l_f — filter length, m; V_f - permissible filtration rate, m/day.

The permissible filtration rate limited by the phenomenon of suffusion is determined by the formula for loose packing:

$$V_f = 1000K \left(\frac{d_{50}}{D_{50}} \right)^2,$$

Where K – filtration coefficient, m/day; D_{50} - the average particle diameter of the packing, mm; d_{50} - average particle diameter of soil, mm.

In our case, the average filtration coefficient is taken ≈ 10 m/day.:

$$V_f = 1000 \cdot 10 \left(\frac{1}{10} \right)^2 = 100 \text{ m/day}$$

According to other formulas, for example formula of S. K. Abramov, V_f is higher and is 140 m/day. Let's take the permissible filtration rate of 120 m/day. [14]. With a well flow rate of 50 m³/h, the daily flow of the well is 1200 m³/day. The diameter of the well is taken 273 mm.

With known Q and V_f , the filter length will be

$$L_f = \frac{1200}{3,14 \cdot 0,273 \cdot 120} = 11,5m.$$

Given a minimum speed of 0.03 m/s, we determine the diameter of the filter with the same capacity of 50 m³/h (0.014 m³/s). Wire filter with a gap size of 2 mm, apen ratio of 20%.

$$D = \frac{0,014}{3,14 \cdot 11,5 \cdot 0,2 \cdot 0,3} = 64mm.$$

The obtained value cannot be accepted, because, firstly, the condition of the permissible upward velocity in the upper section of the filter ($v_f < 1.5$ m/s) is not satisfied, and secondly, the recommended minimum filter diameter is 150 mm, which is dictated by conditions of development and regeneration of wells.

Taking the filter diameter of 150 mm, we will make sure that the condition $v_f < 1.5$ m/s is met, and the entrance velocity will be lower than recommended and will be 0.015 m/s. This allows for shorter filter lengths. If we determine L_f at $D = 0.15$ m and $V_{entrance} = 0.03$ m/s, the optimal filter length will be 5 m.

Thus, with a filter length of about 5 m, a diameter of 150 mm, and an average filtration coefficient of 10 m/day, the well provides a flow rate of 50 m³/h. However, at the place of installation of the filter, the granulometric composition of the sands is characterized by a large size and a greater filtration coefficient than is adopted for the single Quaternary-Cenomanian-Aptan aquifer. In operational terms, this aquifer for water wells is difficult to use as a single one, since it is heterogeneous in geology and filtration properties in depth. The inflow to the filter will be significantly greater in the place of its installation, which provides a large supply of filter capacity.

For the installation of the filter, filtration wire of circular cross section is usually used in practice. According to Table 2, drop-shaped and elliptical wires have the lowest hydraulic resistance value. Due to the complexity of manufacturing a wire with an elliptical cross-sectional shape, we compare the performance values of filters with filtration wire of round Q_r and drop-shaped cross section Q_{dr} . For $\beta_r = 1.73$, $\beta_{dr} = 0.87$ and all other things being equal, we get:

$$Q_r = F \sqrt{\frac{2\Delta p}{\beta_r k_1 \sin \theta \rho}} = F \sqrt{\frac{2\Delta p}{1,73 k_1 \sin \theta \rho}} = 1,08 F \sqrt{\frac{\Delta p}{k_1 \sin \theta \rho}} \quad (5)$$

and

$$Q_{dr} = F \sqrt{\frac{2\Delta p}{\beta_{dr} k_1 \sin \theta \rho}} = F \sqrt{\frac{2\Delta p}{0,87 k_1 \sin \theta \rho}} = 1,52 F \sqrt{\frac{\Delta p}{k_1 \sin \theta \rho}} \quad (6)$$

Making the transformations with formulas (4) and (5), we obtain

$$Q_{dr} = \frac{1,52}{1,08} Q_r = 1,41 Q_r .$$

The performance of filters with a filtration wire of a drop-shaped cross section increases 1.41 as compared with a filter with a round wire.

5 Conclusion

The choice of a water supply system for individual consumers from borehole water intakes is the key to normal operation and maintenance of buildings. The definition of the main parameters of the filters should be carried out at the stage of the water supply project.

Operation and repair of well water pipelines depends on the correct design of the filter and equipment, taking into account local hydrogeological conditions.

The proposed method of selecting the optimal diameter and length of the borehole filter of a water intake well will optimize the operation of the water supply system. The example of filter parameters selection for the hydrogeological conditions of Kursk showed that the use of the entrance velocity criterion in the design of wells can significantly reduce the cost of well construction while ensuring the design flow rate and acceptable lowering of the water level.

The capacity of filters with a filtration wire of a drop-shaped cross-section exceeds that of filters with round-shaped wire by almost one and a half times. The use of a filtration wire of a drop-shaped cross-section will reduce hydraulic losses during the flow of fluid through the filter, consequently, improve the performance of a water well, and thus reduce capital costs by increasing the operational periods between overhauls.

References

1. A.G. Kopanskii, Vestnik grazhdanskih inzhenerov **5(52)**, 110-1182 (2015)
2. Russian Federation Standard SanPin 2.1.4.1074-01
3. A.A. Akul'shin, V.I. Shcherbakov, V.S. Pereverzeva, Promyshlennoe i grazhdanskoe stroitelstvo **4**, 90-94 (2017)
4. V.G. Teslja, Vodospabzhenie i sanitarnaja tehnika **10-2**, 32–36 (2009)
5. I.E. Idelchik, Spravochnik po gidravlicheskim soprotivleniyam (Mashinostroenie, Moscow, 1992)
6. Russian Federation Standard SP 31.13330.2012
7. V.S. Alekseev, Vodospabzhenie i sanitarnaja tehnika **3**, 4–12 (2014)
8. V.S. Alekseev, V.G. Teslja, Vodospabzhenie i sanitarnaja tehnika **11**, 21–28 (2009)
9. V.S. Alekseev, Vodospabzhenie i sanitarnaja tehnika **8**, 34–37 (2008)
10. *Gidrogeologicheskie issledovanija na vodozaborah Kurskoj oblasti s cel'ju vyrabotki rekomendacij po ih optimal'noj ekspluatacii* (Otchetpo NIR, Belgorod, 2006)
11. V.I. Shcherbakov, A.A. Akul'shin, *Vodozabornye sooruzhenija iz podzemnyh istochnikov* (LAP Lambert Academic Publishing, Saarbrucken. Germany, 2017)
12. A.V. Bachmetyev, *Proektirovanie vodozabornyh sooruzhenij iz podzemnyh istochnikov. Metodicheskie ukazaniya* (Voronezgos. Arch. Str. Universitet, 2005)
13. A.A. Akul'shin, V.P. Petrechenko, I.S. Shalaj, Izvestija Jugo Zapadnogo gosudarstvennogo universiteta. Serija: Tehnikaitehnologii **2(3)**, 207–210 (2012)