Design of interacting wells for optimization of investments and operating costs while constructing water-diverting structures

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Abstract. Constructions for water withdrawal are the constitutive building industry component. The cost of these constructions is rather high. That is why while designing it is necessary to choose optimal design model and operating conditions during design life. Operation experience showed that the wells are desirably placed along one line to provide the most optimal conditions for water withdrawal. While designing the wells interaction is considered as a group operation if the distance between them is less than two radiuses of influence. Such wells disposition allows reducing the area and cutting down the investments for water withdrawal construction and also creating the better conditions for equipment and mains operation. Design of interacting wells consists of finding the tube well number, the distance between them, the discharge and levels (static and dynamic). At operating condition determination, it is necessary to consider the combined action of pure water reservoirs and tube well.

1 Introduction

Water withdrawal wells consisting of several tube wells are used for settlements with a great amount of drinking water discharge consumption.

Operation experience showed that it is desirable to place the wells along one line to provide the most optimal conditions for water withdrawal [1,2,6,10,16]. The wells interaction is designed if the distance between the wells is less than 2R that is they work as group ones. Such wells disposition allows reducing the area and cutting down the investments for water wells construction and creating the better conditions for equipment and mains operation. However, because of their influence on each other the wells discharge comes down.

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2 Methods

The design of the interacting wells is in determining the number of tube wells, the distance between them, water discharge and levels (static and dynamic).

The design is done in the following order [3,7,8,12,17]:
1) determine the water discharge for one well \( Q_w \);
2) determine the well radius of influence \( R \) (the distance from the center to the point of static level recovery according to the formula

\[
R = 1.5 \sqrt{at};
\]

\( w \) – pressure conductivity factor \( \text{m}^2/\text{day} \).

Suitable for:
- confined water strata
  \[
  a = k_f \frac{M}{\mu};
  \]
  \( k_f \) – water yield factor;
- free flow strata
  \[
  a = k_f \frac{h_{av}}{\mu};
  \]
  \( h_{av} \) – mean power of waterbearing stratum during the period of pumping, \( \text{m} \); \( h_{av} = 0.8H \);
  \( t \) – standard time of well operation, \( \text{years} \) (25 years = 9125 \( \text{days} \)).
3) interacting well discharge is designed by formula

\[
Q_{in} = \alpha_{in} \cdot Q_w;
\]

where \( \alpha_{in} \) – interaction factor, for practical calculation is taken according to the table 1.

| Distance between wells \( l \), \( \text{m} \) | 2 \( R \) | \( R \) | 0.5 \( R \) | 0.2 \( R \) | 0.02 \( R \) | 0.002 \( R \) |
|---|---|---|---|---|---|---|
| \( \alpha \) | 1 | 0.97 | 0.9 | 0.81 | 0.64 | 0.53 |

4) distance between wells is determined according to the table 2.

| Water-bearing rock | Well productivity, \( \text{m}^3/\text{hour} \) |
|---|---|---|
| | Up to 20 | 20-100 | 100-500 |
| Fine sand | 50 | 50-70 | 70-100 |
| Medium sand | 70-100 | 100-150 | 120-150 |
| Coarse-grained sand | 100-120 | 120-150 | 150-200 |
| Gravel and fractured ground | 120-150 | 150-200 | 200-250 |

5) the number of operating wells is determined by the formula

\[
n = \frac{Q}{Q_{in}};
\]

where \( Q \) – the necessary discharge of water intake, \( \text{m}^3/\text{day} \).

The number of redundant wells is determined according to the table 3.

6) actual discharge (\( \text{m}^3/\text{day} \)) interacting wells is determined according to the number of workers and needed discharge.
7) level lowering, m

- lowering level in each well:

\[ S = \frac{0.37Q_{w1}gR}{k_r} + \frac{Q_{w2}gR}{r_{2-1}} + \frac{Q_{w3}gR}{r_{3-1}} + \cdots + \frac{Q_{wi}gR}{r_{i-1}}; \]  

where \( r_0 \) – well radius, in which the lowering is determined, m;
\( r_{2-1}, r_{3-1}, \ldots, r_{i-1} \) – distance from well № 1 up to the following wells, m.

Thus, the power of water bearing strata and filtration factor are the same on the whole water intake, the productivity of the pump equipment assembled in every tube wells is equal that is well discharges are equal.

8) then the designed maximal lowering is compared \( S_{\text{max}} \) with allowable lowering \( S_{\text{val}} \). At \( S_{\text{max}} > S_{\text{val}} \), widen the distance between wells and repeat the calculations.

The allowable level lowering depends on the hydrological conditions of water bearing strata, tube well structure (well), place of pumping aggregate and filter position. This lowering is determined depending on the producing strata pressure by the following formula:

- in pressure water well \( S_{\text{val}} = H - [(0.3-0.5)M - \Delta h_p - \Delta h_f]; \)  
- free flow strata \( S_{\text{val}} = (0.5 - 0.8) H - \Delta h_p - \Delta h_f \)  

where \( \Delta h_p \) – maximal depth of pipe edge immersion under dynamic level in the well, m; \( \Delta h_f \) – in nonpressure well at inlet through the filter, m.

9) in conclusion, the dynamic level position in the well is determined:

\[ Z_d = Z_{\text{st}} - S_t \]  

where \( Z_d \) – dynamic level, m;
\( Z_{\text{st}} \) – static level, m;
\( S_t \) – accepted value of level lowering, m.

Design of water lifting station consists of some stages:

- substantiation of design model;
- determination of plot size for the water station;
- substantiation of rational scheme of well position inside the plot;
- substantiation of well operation during the design working period (discharge and dynamic level lowering).

Linear scheme of well connection to the prefabricated water conduit is the simplest and applied during the water conduit stringing into one line [4,5,9,11,13] (Fig. 1). Prefabricated water conduct diameter can increase, at growing of joined wells number and as a result at the discharge increase.
While determining the prefabricated water conduit operation behavior it is necessary to take into consideration the combined work of pure water tanks and tube wells. Thus, the pressure created by submersible drive pump unit at the point of connection to the prefabricated water conduit $H_1$ should be greater than in water conduit.

In Fig. 2 there is the scheme with well point systems applied as water diversion works. Water derived from water bearing strata by submersible pumps is placed in wells into pressure water conduits delivered into collection water conduit and then comes into pure water tanks.

General scheme of structures disposition on water system presented in draw 2 is the most commonly used in construction practice and underground water-diverting structure operation when wells are used as water receiving structures as the quality of water extracted from water bearing strata before delivery to a consumer needs improving.

If on the water-diverting structure the amount of wells are big and they are located along a river and on the distance $L$ from it, it is possible to use formula admitting the substitution of real well raw, by the galleries with 1m of length discharge [4,14, 15,16]:
where \( Q_\Sigma \) - total discharge of wells; 
\( Q \) – one well discharge;
\( l \)- half the gallery length;
\( \sigma \) - half the distance between wells; \( \sigma = \frac{l}{n-1} \);
\( n \) – general number of wells.

If the linear series of wells has a length commensurate with the distance to the river (that is \( 2l \approx L \)), the equation for a gallery of finite length is used in the calculations. Then, when using a method of mirror displays, we receive the dependence allowing to define decrease in dynamic level at any time, time at the long periods pumping out to any point of layer \( M \) (draw. 3).

If the linear row has the length commensurable with the distance up to a river (that is \( 2l = L \)), the equations for the galleries of final length are applied [17,18]:

\[
S = \frac{Ql}{2\pi \sigma R_{lin}}
\]  

(13)

\[
R_{lin} = \frac{1}{2} \ln \frac{1 + (\frac{y}{L} + \frac{L}{L})^2}{1 + (\frac{y}{L} - \frac{L}{L})^2} - \frac{1}{y} \arctg \frac{2L}{y^2 - L^2 + 1} + \frac{1}{y} \arctg \frac{2y}{y^2 - L^2 - 1}
\]  

(14)

These formulas give the possibility to determine how the dynamic level falls at points remote from the wells located perpendicularly to it.
If it is demanded to determine the dynamic level lowering in the very tube wells the function \( R_{lin} \) is expressed as following:

\[
R_{lin} = \frac{1}{2} \ln 1 + (1 + 2\bar{L}) + 21 + \bar{L} \arctg \frac{1}{2L} + \frac{2\bar{\sigma}}{L} \ln \frac{\sigma}{\sigma_0} + \zeta
\]  

(15)

Simply transforming the formula (12) and putting formula (14) into it we receive the dependence with the help of which we define the water discharge of one well:

\[
Q = \frac{2S \pi \sigma \sigma \sigma}{l} \left( \frac{1}{2} \ln 1 + (1 + 2\bar{L}) + 21 + \bar{L} \arctg \frac{1}{2L} + \frac{2\bar{\sigma}}{L} \ln \frac{\sigma}{\sigma_0} + \zeta \right)
\]  

(16)

Fig. 3. Scheme of the design of linear row of wells locating near the river.
As a result, we receive the general dependence of discharge for one well:

\[
Q = \frac{4\pi k m \sigma S}{-E_i\left(-\frac{r^2}{4at}\right) + \varepsilon}
\]  

(17)

k - filtration factor, m/day;  
m - water bearing horizon power, m;  
t - duration of water pumping from one well  
R - well radius, m;  
a - pressure conductivity factor  
Ei - integral exponential function;  
\varepsilon - factor considering filter resistance, considering hydraulic uplift.

If wells give the constant discharge during long period of operation the expression (17) is

\[
Q = \frac{2\pi k m \sigma S}{\ln \frac{R}{r} + \varepsilon}
\]  

(18)

R - well radius of influence.

If during the water intake the wells are located in one row and parallel to water body bank the calculation can be done by the expression:

\[
Q = \frac{2\pi k m \sigma S}{\ln \sqrt{1 + \frac{2L}{l} + \frac{2L}{l} \arctg \frac{l}{2L} + \frac{\sigma}{\pi l} \left(\ln \frac{\sigma}{\pi l} + \varepsilon\right)}}
\]  

(19)

L - distance between the rows of wells, m.

3 Results

Investments for building and creation of the best conditions for the equipment and mains operation depend on the choice of the scheme of water-diverting structure, its operation performances.

The analysis of optimization of interacting wells operation showed that linear scheme of tube wells connection to the collection water conduit water conduit is the simplest one and is used while water conduit placing in one row.

4 Discussion

The design of interacting wells group consists of defining the tube wells number, distance between them, discharge and levels (static and dynamic). While determining the operation conditions of water collection conduit it is to consider combined work of pure water tanks and tube wells.

The diameter of water collection conduit is to be increased at increasing of connected wells number and consequently the increasing of discharge.

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