Use of Ground Water for Irrigation*

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It is expedient to use ground water for irrigation mainly near reservoirs on lowland rivers, where a large amount of fresh water accumulates in the zone of aeration as a result of infiltration, and new aquifers sometimes form. At the present time, the total volume of reservoirs constructed on the rivers of the USSR is 400 km^3 (about 10% of the mean annual runoff of Soviet rivers). According to rough estimates, from 40 to 60 km^3 of water has accumulated in the backwater zone of these reservoirs.

In addition, it is very efficient to irrigate land with ground water in the foothills and intermontane basins consisting of alluvial deposits, as well as in river valleys with permeable alluvium (particularly when it is represented by gravelly-pebbly, sandy-pebbly, and sandy-gravelly deposits). Under these conditions, irrigation with ground water does not require the construction of dams, water intakes, arterial canals, and of an irrigation network. The water from wells and spare storages in relief depressions is delivered directly to low-order irrigators, whence it is drawn by sprinkling machines. In that case the intake wells of the irrigation system also perform the function of vertical drainage, producing a leaching irrigation regime and preventing the salinization of the land.

Most promising is the combined use of surface and ground waters for these purposes. This kind of irrigation is applicable wherever ground water is fresh or even slightly mineralized (5-6 g/liter). It is most expedient to use only surface water for irrigation in wet years and to store its surplus in underground aquifers, and to use both surface and ground waters in dry and normal years.

The optimum ratio between the annual utilization of ground q and surface q_1 waters (m^3/hectare) for irrigation over the long range with various long-period mean values of precipitation infiltration ε is expressed by the following relation:

$$\beta = \frac{q}{q+q_1} = \frac{(1-\alpha_1)C+\varepsilon}{(1-\alpha_1)C+\alpha C}, \qquad (1)$$

where α is the efficiency of systems during irrigation with ground water; α_1 is the same during irrigation with surface water; and C is the average annual irrigation rate (gross), amounting to 10,000 m^3 per hectare = $2{,}74\cdot 10^{-3}$ m/day for the irrigated regions of the USSR.

Table 1 gives the values of β, computed by formula (1). We can see that ground-water utilization for the best irrigation systems ($\alpha_1=0{,}85$—$0{,}90$; $\alpha=0{,}90$—$0{,}95$) varies within 14-33% of the total water withdrawal for irrigation. At the present time, about 140-150 km^3 of water a year are used in the USSR to irrigate 14.5 million hectares. Consequently, it is expedient to use 20-45 km^3 of ground water a year for irrigation in operating systems alone (provided their efficiency is improved). One could irrigate 2 to 4 million hectares with this water.

When underground water intakes are used for irrigation, one must observe the drop in water level in the wells as they are being used and determine the effect of the operation of the given water intake on other water intakes and also the change in the quality of the ground water during its exploitation.

The yield (efficiency) of water intakes can vary depending on the drop in water level in the wells. The maximum efficiency of a water intake corresponds to the maximum allowable drop in water level S_m and is the exploitable resource of a given water intake. The maximum allowable drop in level S_m is equal to the difference in elevation between the static level and the base of the aquifer.

Two kinds of maximum intake output should be distinguished:

a) Constant guaranteed output Q_s, equal to the yield of the water intake with a maximum drop in level S_m under a steady infiltration regime. It includes only external inflow to the intake, i.e., inflow resulting from the infiltration of precipitation, irrigation or other waters, and also the infiltration of water from recharge regions.

b) Temporary guaranteed maximum output $Q_0(t_0)$, equal to the yield of the intake at which a maximum drop in level S_m is reached by the end of a given operating period t_0 under unsteady infiltration conditions. In addition to external inflow to the water intake, the yield Q_0 includes the drawdown of static supplies. Therefore, $Q_0 > Q_s$ and is independent of the duration of exploitation of the water intake and decreases with increasing t_0 (as $t_0 \to \infty$, $Q_0 \to Q_s$).

If water is drawn from an aquifer at a constant rate $Q \leqslant Q_s$, the water level in the well drops continuously to a maximum corresponding to a stationary infiltration regime. Under these conditions, the output of the water intake will not decrease during exploitation and the aquifer will not be exhausted. Such operating conditions can be called normal.

If, however, the water is drown off an aquifer at a rate $Q > Q_s$, the water level in the wells drops more rapidly than in the first case and reaches the value of S_m at a certain instant of time. The output of the water intake will decrease from this instant on, and to provide for a given water consumption one has to put new wells into operation or recharge the ground water with surface water using infiltration basins and by pumping water into the aquifer through wells. Under

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Table 1

Values of β for Various Long-Period Mean Values of Precipitation Infiltration

α \ α_1	0,55	0,75	0,85	0,90
		$\varepsilon = 1,37 \cdot 10^{-4}$ m/day		
0,67	0,4464	—	—	—
0,80	0,4	0,2857	—	—
0,90	0,3704	0,2608	0,1905	0,15
0,95	0,3572	0,25	0,1818	0,1429
		$\varepsilon = 2,74 \cdot 10^{-4}$ m/day		
0,67	0,4911	—	—	—
0,80	0,44	0,3333	—	—
0,90	0,4074	0,3043	0,2381	0,2
0,95	0,3929	0,2917	0,2273	0,1905
		$\varepsilon = 5,48 \cdot 10^{-4}$ m/day		
0,67	0,5904	—	—	—
0,80	0,52	0,4286	—	—
0,90	0,4818	0,3913	0,3333	0,3
0,95	0,4643	0,375	0,3182	0,2857

these conditions the aquifer becomes somewhat depleted, starting from the instant t_0. Such operating conditions can be described as forced.

Suppose that the water intakes are located in permeable rocks with a sufficiently high water yield within the entire aquifer (or hydrogeological aquifer complex), bounded in plan by bodies of water and from below by a regional impervious bed overlying aquifers with mineral water. Let us assume that these intakes satisfy the following requirements: (i) groups of wells and individual wells are located in the given rocks at optimum (technically and economically speaking) distances from each other (l) and from bodies of water (l_1), and (ii) the water in the intakes and wells retains its properties that satisfy the state standards during operation over a given reference time t_k.

The total output of such intakes ΣQ_s, corresponding to a maximum drop in water level in wells S_m, characterizes the exploitable resources of a given aquifer that are completely renewable and constantly guaranteed.

The total output of intakes $\Sigma Q(t_0)$, corresponding to a drop in water level S_m by the end of the operating period t_0, however, characterizes the exploitable resources of an aquifer, which are only partly renewable and guaranteed only over a period $t_0 (\Sigma Q_0 > \Sigma Q_s)$.

The exploitable resources of water intakes of both kinds increase considerably with the construction of dams on rivers.

One must distinguish between water intakes located near bodies of water (rivers, lakes, reservoirs) and at a distance from them. The output of both is expressed by the relation:

$$Q = Q_{st} + Q_{inf} + Q_p, \qquad (2)$$

where Q_{st}, Q_{inf}, and Q_p are the inflows to the intakes resulting from the drawdown of static supplies, infiltration of precipitation, irrigation and other waters, and pumping from bodies of water.

When wells are uniformly distributed over the area of an aquifer (at optimum distances from each other), the inflow from bodies of water Q_p will be significant for wells that are closest to them and small for wells at a distance from them.

We will investigate the variation in the components of the output of a water intake, Q_{st}, Q_{inf}, and Q_p, during its operation. To this end we will analyze a typical water intake consisting of a long row of wells near some open body of water. To simplify the computations we will replace this row by a gallery exposing the aquifer throughout its depth.

The drop in level at any point of the aquifer during the pumping of water from several wells with a constant output is determined from the formula

$$S_{1,2} = \frac{ql_1}{km} \sqrt{\tau} \left(i \operatorname{erfc} \frac{1 - \bar{x}}{2\sqrt{\tau}} - i \operatorname{erfc} \frac{1 + \bar{x}}{2\sqrt{\tau}} \right), \qquad (3)$$

where $\tau = at/l_1^2$; $x = x/l_1$; $q = Q/l$; $S_1, = h_e - h_1$; S_1 is the drop in level in zone I ($0 \leq x \leq l_1$); S_2 is the same in zone II ($l_1 \leq x \leq \infty$); l_1 is the distance from the river to the water intake; km is the conductivity of the aquifer; Q is the well output; l is the distance between the wells; a is the piezoconductivity; h_1 and h_2 are the heads in zones I and II; $h_e(x)$ is the head of the natural groundwater flow in the same zones; and t is time.

When determining the drop in water level in the wells themselves, $\bar{x} = 1$ in (3) and then we have

$$S_0 = \frac{ql_1}{km} \sqrt{F_0} \left(0{,}564 - i \operatorname{erfc} \frac{1}{\sqrt{\tau}} \right) + \frac{Q}{2\pi km} \ln \frac{l}{2\pi r_0}. \qquad (4)$$

where r_0 is the well radius.

The head of the natural flow h_e is expressed as:

$$h_e = h_0 + \frac{q_0}{km} x - \frac{1}{2} \frac{\varepsilon}{km} x^2. \qquad (5)$$

Here h_0 is the head at the river ($x = 0$); q_0 is the discharge of the natural flow in the cross section $x = 0$ (when the flow is directed toward the river $q_0 > 0$ and

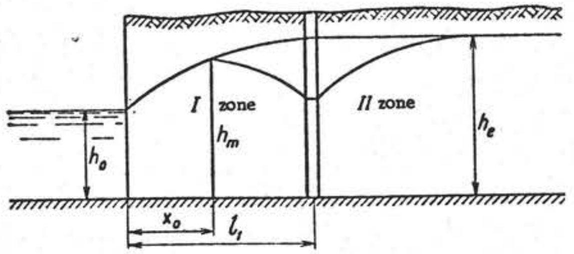

Fig. 1. Working diagram of the seepage of water toward a water intake near shore.

when it is directed away from it $q_0 < 0$); ε is the rate of recharge by infiltration; m is the thickness of the confined aquifer for a flow with a free surface $m = 0.5\ (h_e + h_0)$.

With allowance for (4), the head between the river and the water intake ($0 \leqslant x \leqslant l_1$) is determined from the formula

$$h_1 = h_0 + \frac{q_0}{km}x - \frac{1}{2}\frac{\varepsilon}{km}x^2 - S_1(x, t), \qquad (6)$$

where $S_1(x, t)$ is expressed in accordance with (3).

When water is pumped from the wells, a maximum head h_m forms between the body of water (recharge region) and the row of wells (Fig. 1). In the region bounded by the cross section with the maximum head h_m and the row of wells, infiltration water flows into the wells and, therefore, this region is called the water-capture zone of the intake. In the region between the same cross section and the body of water, infiltration water flows into the latter (zone of recharge of the body of water). The width of this zone is determined from (6) under condition $dh_1/dx = 0$ and is expressed as:

$$x_0 = \frac{q_0}{\varepsilon l_1} - \frac{q}{2\varepsilon l_1}\left[\operatorname{erfc}\frac{1-\bar{x}_0}{2\sqrt{\tau}} + \operatorname{erfc}\frac{1+\bar{x}_0}{2\sqrt{\tau}}\right]; \quad \bar{x}_0 = \frac{x_0}{l_1}. \qquad (7)$$

The width of this zone x_0 decreases with time, while that of the water-capture zone of the intake $l_1 - x_0$ increases. The infiltration of water from the river into the water intake begins at the instant t_1, when $x_0 = 0$. Taking $x = 0$ in (7), we find the time of the beginning of infiltration from the river:

$$\tau_1 = \frac{1}{4\,(\operatorname{arc\,erfc}\bar{q}_0)^2}, \quad \bar{q}_0 = \frac{q_0}{q}. \qquad (8)$$

The flow rate at a distance x from the river ($0 \leqslant x \leqslant l_1$) will be

$$q_x = km\frac{\partial h_1}{\partial x} = -q_0 + \varepsilon x - \frac{1}{2}q\left[\operatorname{erfc}\frac{1-\bar{x}}{2\sqrt{\tau}} + \operatorname{erfc}\frac{1+\bar{x}}{2\sqrt{\tau}}\right]. \qquad (9)$$

Taking $x = 0$ in (7), we get the flow rate q_p from the aquifer into the river ($x_0 > 0$) or the flow rate from the river into the aquifer ($x_0 = 0$)

$$q_p = q_0 - q\operatorname{erfc}1/2\sqrt{\tau}. \qquad (10)$$

From (8) it follows that when $x > 0$, $t > 0$, the flow rate into the river decreases by a value $q\operatorname{erfc}{}^1/_2\sqrt{\tau}$ by comparison with the flow rate under natural conditions ($t = 0$, $q_p = q_0$). Water inflow from the river is possible only when the second term in the right-hand part of (8) is greater than the first. When $q \leqslant q_0$, inflow from the river is altogether impossible.

The inflow from the first zone ($0 \leqslant x \leqslant l_1$) into the water intake is found from (9) for $x = l_1$, ($x = 1$), and the value of q_0 from (8)

$$q_1 = q_p - q\operatorname{erfc}\frac{1}{2\sqrt{\tau}} + \frac{1}{2}q\left(1 + \operatorname{erfc}\frac{1}{\sqrt{\tau}}\right) + \varepsilon l_1 =$$
$$= q_p + \frac{1}{2}q\left(1 - \operatorname{erfc}\frac{1}{\sqrt{\tau_0}}\right) + \varepsilon l_1. \qquad (11)$$

We can see from (11) that the inflow into the water intake from zone I due to static reserves is

$$q_{st} = {}^1/_2 q\left(1 - \operatorname{erfc}1/\sqrt{\tau}\right), \qquad (12)$$

to recharge by infiltration it is

$$q_{inf} = \varepsilon(l_1 - x_0),\ (x_0 > 0);\ q_{inf} = \varepsilon l_1,\ (x_0 = 0) \qquad (13)$$

and the inflow from the body of water, q_p, is that determined from (10).

Computations by formula (7) for $q_0/q = \varepsilon l_1/q = 0{,}1$ show that the width of the river recharge zone x_0 and the width of the water-capture zone of the intake $l_1 - x_0$ vary as a function of τ as shown in Table 2.

Figure 2 gives the values of $\bar{q}_{st}$, $\bar{q}_{inf}$, $\bar{q}_p$, and $\bar{q}_1$ computed from formulas (7), (12), and (13) for $q_0/q = \varepsilon l_1/q = 0{,}1$ and different values of dimensional time τ ($q_{st} = q_{st}/q$; $\bar{q}_{inf} q_{inf}$; $\bar{q}_p = q_p/q$; $\bar{q}_1 = q_1/q$).

As we can see, during the initial period of pumping ($0 < \tau < 0{,}2$), the water intake is fed mainly by static supplies (curve 1 in Fig. 2). Then, as τ increases

Table 2

Variation of the Values of x_0 and $1-x_0$ as a Function of the Value of τ

τ	10^{-3}	10^{-2}	10^{-1}	0,192
$\bar{x}_0$	0,894	0,728	0,324	0
$1-\bar{x}_0$	0,106	0,272	0,676	1

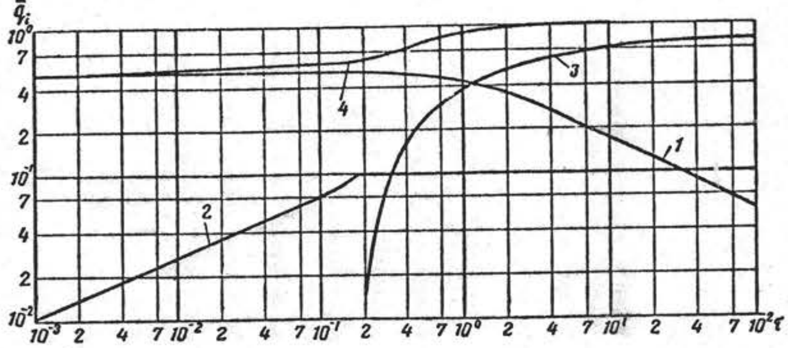

Fig. 2. Plots of the dependence of 1) $\bar{q}_1$; 2) $\bar{q}_{st}$; 3) $\bar{q}_{inf}$; 4) $\bar{q}_p$ on the parameter τ.

from 0.2 to 10^2, the static supplies decrease from 0.5 to 0.056, i.e., by a factor of almost 10.

The recharge of the water intake by infiltration $\bar{q}_{inf}$ (curve 2 in Fig. 2) changes from 0 ($\tau=0$) to 0.1 ($\tau=0{,}192$) and remains constant thereafter.

Seepage from the body of water $\bar{q}_p$ begins at $\tau = 0.192$ and subsequently increases sharply, reaching a value of 0.84 at $\tau=10^2$ (curve 3 in Fig. 2).

The total inflow to the water intake from zone I, $\bar{q}_1$ (curve 4 in Fig. 2) at the beginning of pumping ($\tau<0{,}1$) consists of the drawdown of the static supplies of the aquifer and equals about half of the output of the water intake q. As inflow from the body of water begins, the output $\bar{q}_1$ increases and reaches 0.9 at $\tau=1$. The proportion of infiltration water in this inflow is 11%, that of static supplies 47%, and that of river water 42%.

Subsequently the loss of river water increases and at $\tau=10^2$ it amounts to 84% of the value of $\bar{q}_1$. At this instant, the inflow to the water intake is almost completely due to seepage from zone I.

Thus, the loss in river runoff in zone I, caused by the withdrawal by underground water intakes of the water that used to flow into the river q_{inf} and by seepage from the river $\bar{q}_p$ when $\tau\approx 0{,}2$, is only 10%. when $\tau = 1$, this loss increases sharply and reaches 53%. Subsequently it continues to increase, but relatively slowly and reaches 94% when only $\tau = 100$. This loss is smaller in zone II, where the river is at a great distance.

At the present time, the requirement in drinking water supply is met mainly by surface water. If we assume that by the year 2000 half of the population of regions with available ground-water resources will use this water as the best water supply source and that the average water consumption rate will reach 400 liter per day by that time, the expenditure of ground water for these purposes will not exceed 15-16 km^3/year.

The following ground-water sources can be used for irrigation without detriment to the water supply of the population: up to 30-35 km^3/year of renewable dynamic reserves and up to 30 km^3/year of static reserves.

The annual use of 60-65 km^3 of ground water for irrigation (at the average irrigation rate for the USSR) will make it possible to irrigate about 6-7 million of hectares. The use of progressive irrigation methods (drop, aerosol, subsoil irrigation), the distribution of irrigation water over a close system, and better field planning will reduce the irrigation rate (gross) by at least 15-20%. This will make it possible to increase the area under irrigation by ground water to 7-8 million hectares instead of the 0.9 million hectares irrigated now.