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DETERMINING THE EFFICIENCY OF RADIANT WATER INTAKES WITH REGARD TO LOSS OF ENERGY IN COLLECTORS

The methods allowing us to take account of energy losses in the collectors in calculation of basic characteristic of the efficiency of infiltrating water radiant intakes are given. The algorithm of numerical calculations according to Newton method is presented and used to work out the „DREN" program in the Fortran language for a computer Odra 1300. An example of application of the methods, according to which $s_p = Q_u$ was calculated to determine the efficiency of a radiant intake in Warsaw, is given. It has been stated that the results obtained for the efficiency of infiltrating water radiant intakes calculated according to the formulae of Surow and Maciejewski, in which the regarding losses of energy in the collectors were taken into account, are similar to the results of pumpings.

NOTATIONS

a – empirical coefficient, the value of which for perforated filters ranges from 9 to 15,

c – coefficient of silting-up characterizing seal degree for river ($0.5 \leqslant c \leqslant 0.6$),

Δh_f – hydraulic losses due to water flow through the filter surrounding the collector [m],

Δh_s – hydraulic losses due to water flow inside the perforated and non-perforated segments of the collector, including the losses occurring when water flows into the cumulative well of the intake [m].

k_f – filtration coefficient of aquiferous layer [m/s],

k_{f0} – coefficient of silted up filtration of demersal ground layer [m/s],

k_z – equivalent sand roughness according to Nikuradse [m],

l_f – length of the collector's perforated part [m],

l_0 – length of the collector's non-perforated part [m],

n – number of collectors,

r_0 – inner radius of the collector [m],

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s — real depression outside the cumulative well [m],
s_p — apparent depression inside the cumulative well [m],
z — depth of the collector under the bottom of river [m],
B — dimensionless empirical coefficient for $\varphi \geqslant 0.10$, $B \cong 1.0$,
D — outer diameter of the cumulative well of the intake [m],
H — depth of river water [m],
H_w — thickness of aquiferous layer [m],
L — total length of the collector: $L = l_f + l_0$ [m],
R — equivalent radius of the natural filter round the collector [m],
Q_u — efficiency of the intake [m^3/s],
α — coefficient of interaction of the collectors,
β — angle between the collectors [rad],
λ — coefficient of linear resistance in a non-perforated pipe,
ν — coefficient of kinematic viscosity of water [m^2/s],
φ — permeability of perforated wall of the pipe (collector).

1. INTRODUCTION

The paper deals with infiltrating radiant intakes with level collectors placed under the bottom of river or under a surface water tank. The efficiency of this intake type depends on many factors characterizing hydrogeological and operation conditions as well as the intake's structure:

$$Q_u = F(H_w, k_f, k_{f0}, s, s_p, l_f, n, r_0, \varphi, z).$$

These quantities (except for k_{f0}, s_p, φ) occur in most of the formulae used for calculations of the efficiency of this intake type, though they are dealt with in these formulae differently.

Calculations of the efficiency of radiant water intakes, based on most often used currently Razumow, Surow, Ostrowski and Połubarinowa–Koczina formulae, give, as a rule, too optimistic results. Divergences, that may reach 500% [2], [4], [17], result among others from the fact that these formulae do not contain hydraulic losses Δh_f due to a water flow through the natural filter formed around the collectors and through openings made in the wall of the collectors, as well as losses Δh_s caused by the motion of water inside the perforated and non-perforated sections of the collectors (fig. 1). These losses cause that the depression of water level with respect to hydrostatic level, the so-called apparent depression s_p, is much greater than the factual depression (outside the cumulative well), taking place due to hydraulic resistance during infiltration of water through aquiferous layer.

This fact is of essential importance when the efficiency of radiant intakes is to be calculated because the formulae used at present have a general form $Q_u = f(s)$, and not $Q_u = f(s_p)$ (when water intakes are exploited, factural depression s is not measured). A linear dependence $Q_u = f(s)$ resulting from the most often used formulae is not a true representation of the basic characteristic of the efficiency of infiltrating radiant water intakes [4].

Results of field [15], [16] and model investigations [4], [5], [9] have proved that identification of factural depression s with apparent depression s_p may lead to considerable errors when calculating the efficiency of the intakes discussed.

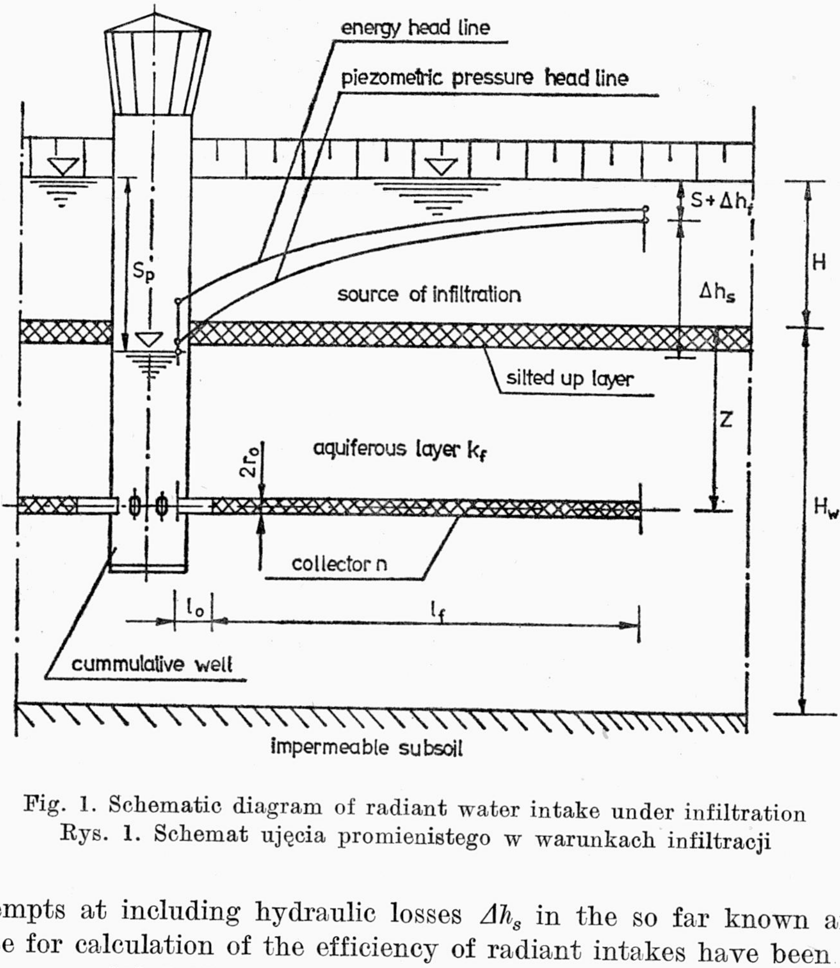

Fig. 1. Schematic diagram of radiant water intake under infiltration
Rys. 1. Schemat ujęcia promienistego w warunkach infiltracji

Attempts at including hydraulic losses Δh_s in the so far known analytic formulae for calculation of the efficiency of radiant intakes have been undertaken in papers [1], [13], [15]–[18]. The authors of most of these papers (except Siwoń, whose formulae are based on results of laboratory tests of loss of energy due to flow of water inside the perforated collector) defined the value of Δh_s approximately, among others as a function of resistance coefficient λ in non-perforated wall pipes. Therefore they obtained different results [14], e.g. calculations according to the formula given in [18] yield two times or three times lower hydraulic losses Δh_s, measured under field conditions by **STEFAŃCZYK** [15] or calculated according to the formulae given by **SIWOŃ** [11]–[14].

Calculations of the characteristic of efficiency $s_p = f(Q_u)$ of infiltrating radiant intakes are very labour-consuming due to a complicated form of initial formulae.

In the present work the algorithm of a computer-aided quick-running method for calculation of this characteristic has been presented.

2. INITIAL FORMULAE

The efficiency of infiltrating radiant water intakes at a finite thickness of aquiferous layer may be calculated among others by means of the formulae of Razumow, Surow and Maciejewski [2]–[4]. According to papers [2], [4], [17], the results of calculations based on the formulae of Razumow and Surow as well as on those of Połubarinowa–Koczina and Ostrowski are in general overestimated with respect to the results of field measurements performed for radiant intake in Warsaw, as well as to the results of model testing. Average differences between the results of calculations and measurements of the factual efficiency of the intake [17] vary from 150% (according to Połubarinowa–Koczina formula) to 25% (according to Surow formula). The results of calculations obtained from the Maciejewski formula have not been compared yet with the results of field or model measurements. According to [3] the efficiency calculated by means of this formula gives results close to those obtained by applying the Razumow formula ($n < 10$).

In the sequel the following analytical formulae will be used:

1. The Surow formula:

$$Q_u = ack_{fp}snl_f\Phi^{-1}[\mathrm{m}^3/s] \tag{1}$$

where a — coefficient of interaction of the collectors ($0.6 \leqslant a \leqslant 1.0$) calculated from the formulae:

$$a = \frac{A}{A + 0.5\sum_{i=1}^{n} K} \tag{2}$$

and

$$A = \ln\frac{2z}{1.225r_0} - \ln\frac{0.5l_f + \sqrt{0.25l_f^2 + 4z^2}}{l_f}, \tag{2a}$$

$$K = \ln \frac{[f+\sqrt{f^2+d^2+4(z+r_0)^2}\,](e+\sqrt{e^2+d^2})}{(f+\sqrt{f^2+d^2})[e+\sqrt{e^2+d^2+4(z+r_0)^2}\,]}, \tag{2b}$$

$$f = R_c - g,$$

$$R_c = l_0 + 0.5D,$$

$$g = a\cos\beta,$$

$$a = 0.5(R_c + L + 0.5\mathrm{D}),$$

$$L = l_f + l_0,$$

$$e = L + 0.5D - g,$$

$$d = a\sin\beta.$$

Vertical filtration coefficient k_{fp} in formula (1) is determined as a weighted average of filtration coefficients of two layers:

a) silted up layer, 0.5 m thick, filtration coefficient k_{fo},

b) lower aquiferous layer, the thickness of which is $H_w = 0.5$ m, and filtration coefficient k_f:

$$k_{fp} = H_w \Big/ \left[\frac{0.5}{k_{f0}} + \frac{H_w - 0.5}{k_f}\right] [m/s]. \tag{3}$$

Coefficient Φ is determined from the formula:

$$\Phi = \frac{1}{2\Pi} \ln \left[\mathrm{tg}\left(\frac{\Pi}{4}\frac{2z+r_0}{H_w}\right)\mathrm{ctg}\left(\frac{\Pi}{4}\frac{r_0}{H_w}\right)\right]. \tag{4}$$

2.The Razumow formula:

$$Q_u = \frac{2.73 k_f s l_f n}{\lg U + \frac{n-1}{2}\lg U_\beta} \; [m^3/s] \tag{5}$$

where:

$$U = \frac{3 H_w z l_f}{r_0 (H_w - z)(l_f + \sqrt{l_f^2 + 16 H_w^2})}, \tag{6}$$

$$U_\beta = 1 + \frac{16 H_w^2}{l_f^2 \sin^2\beta}. \tag{7}$$

Application conditions:

$$0.2 \leqslant \frac{z}{H_w} \leqslant 0.8, \qquad \frac{L}{H_w} > 3,$$

$$z \geqslant 20r_0, \qquad \beta \geqslant 0.393\,(22.5^\circ), \qquad H_w - z \geqslant 2r_0.$$

3. The Maciejewski formula:

$$Q_u = 5.4k_f s l_f n^{0.56} z^{-0.40} H_w^{0.12} r_0^{0.28}\ [\mathrm{m}^3/\mathrm{s}]. \tag{8}$$

Application conditions:

$$\frac{L}{r_0} \geqslant 100, \qquad 15 \leqslant \frac{z}{r_0} \leqslant 310,$$

$$20 \leqslant \frac{H_w}{r_0} \leqslant 415, \qquad 4 \leqslant n \leqslant 16.$$

The formulae of Surow [1], Razumow [5], and Maciejewski [8] have been transformed to the form convenient for a further analysis:

$$s = \frac{Q_u \Phi}{ack_{fp} n l_f}\,[\mathrm{m}], \tag{1a}$$

$$s = \frac{Q_u\left(\lg U + \frac{n-1}{2}\lg U_\beta\right)}{2.73 k_f l_f n}\,[m], \tag{5a}$$

$$s = \frac{Q_u z^{0.40}}{5.4 k_f l_f n^{0.56} H_w^{0.12} r_0^{0.28}}\,[m]. \tag{8a}$$

The value of depression s comprises factual depression s, and the sum of hydraulic losses Δh and Δh. If we assume that analytical depression s given in the formulae (1), (5), and (8) for infiltrating radiant water intake denotes the depression at the beginning of the collectors (fig. 1), then [3], [13], [14]:

$$s_p = s + \Delta h_f + \Delta h_s\,[\mathrm{m}]. \tag{9}$$

Estimation of the value of Δh is much difficult. This value comprises hydraulic losses caused by the change of the area of flow cross-section (at the so-called contact zones that occur e.g. at aquiferous layer and the natural filter interface and also that of the natural filter and the perforated collector), losses due to a water flow through the natural filter zone (including the losses caused by the reverse motion of water jets), as well as the holes in the collector wall [14].

Hydraulic resistance in the near filter zone can increase when water intake is used due to cementation of the bed with deposits of chemical compounds contained in water and to mechanical silting-up. Hydraulic resistance may be additionally caused by overgrowing inlets of the collector (the so-called cementation of inlets), though this process is usually weaker in radiant water intakes than in standard (upright) bored wells [18], [19].

In literature there are no data concerning the value of hydraulic resistance Δh_f in level filters of drains.

By analogy to the level wells, the value of Δh_f may be approximately estimated from the Abramow formula:

$$\Delta h_f = 0.01a\sqrt{\frac{s_p Q_u}{2\Pi nRl_f k_f}}\ [\mathrm{m}] \qquad (10)$$

where R is equivalent radius of the natural filter formed around the collector; it depends mainly on the method of water intake construction. According to Öllös [10]: $R = 1.0$ m – at the Ranney method, $R = 0.6$ m – at the Fehlmann method, $R = 0.25$ m – at the Preussag method.

The value of Δh_s in formula (9) is the sum of hydraulic losses due to a flow of water inside the perforated and non-perforated wall segments of the collectors (including hydraulic resistance during the water inflow to the cumulative well of the intake). Results of field and model investigations obtained so far and presented among others in [6], [7], [15], [16] indicate that in infiltrating radiant water intakes, the water inflow to collectors is distributed uniformly. It is probably due to the fact that in sandless zone which forms a natural filter, the flow of water may be parallel to the axis of collectors. The increased hydraulic resistances of the bottom of infiltration source (silting-up) and that of ground occurring at higher inflow rate, which reduce the possibility of considerable increase of unit intensity of water inflow above the average values for collectors, are additional factors.

The formulae allowing the calculation of the value of Δh_s have been taken from papers [11], [12], [14] in which the problem of hydraulic calculation of perforated collectors has been discussed in detail. For a unifrom distribution of water inflow intensities along the collectors perforated with round holes, these formulae take the following forms:

$$\Delta h_s = \Bigg\{ \frac{17.18 r_0 + \Big[0.0106\varphi^{0.413} + 0.11\Big(\frac{k_z}{2r_0} + 0.282\varphi^{2.40}}{1160.7 r_0^5 n^2}$$

$$+ \frac{\frac{106.76 r_0 \nu n}{Q_u}\Big)^{0.25} B\Big] l_f + 3\lambda l_0}{1160.7 r_0^5 \mathrm{n}^2}\Bigg\} Q_u^2\, [\mathrm{m}] \qquad (11)$$

where λ is linear resistance coefficient of the collector prior to its perforation. The value of coefficient λ may be calculated by means of the Altszul formula [14]:

$$\lambda = 0.11\left(\frac{k_z}{2r_0}+\frac{106.76 r_0 \nu n}{Q_u}\right)^{0.25}. \tag{12}$$

3. FORMULATION OF PROBLEM AND DESCRIPTION OF ALGORITHM

The problem consists in determining with assumed exactness the efficiency Q_u of infiltrating radiant water intake for the given values of depression s_p in the cumulative well according to the formulae of Razumow [1], Surow [5], and Maciejewski [8]. Structure of the intake and hydrogeological conditions are defined. The initial equation has the form:

a) general:

$$s = \Delta h_f + \Delta h_s - s_p = 0, \tag{13}$$

b) detailed:

$$(b_1+b_2)Q_u^2 + C_{1(S,R,M)}Q_u + d_1 Q_u^{0.5} - s_p = 0 \tag{14}$$

where:

$$b_1 = \frac{17.18 r_0 + 0.0106\varphi^{0.413} l_f}{1160.7 r_0^5 n^2}, \tag{14a}$$

$$b_2 = \frac{0.11\left(0.282\varphi^{2.4}+\frac{k_z}{2r_0}+\frac{106.76 r_0 n\nu}{Q_u}\right)^{0.25} l_f + 3\lambda l_0}{1160.7 r_0^5 n^2}, \tag{14b}$$

$C_{1(S,R,M)}$ — coefficients calculated individually:

a) $C_{1(S)}$ according to the Surow formula:

$$C_{1(S)} = \frac{\Phi}{acnl_f k_{fp}}, \tag{15}$$

b) $C_{1(R)}$ according to the Razumow formula:

$$C'_{1(R)} = \frac{\lg U + \frac{n-1}{2}\lg U_\beta}{2.73 k_f l_f n}, \tag{16}$$

c) $C_{1(M)}$ according to the Maciejewski formula:

$$C_{1(M)} = \frac{z^{0.40}}{5.4 k_f l_f n^{0.56} H_w^{0.12} r_0^{0.28}}, \tag{17}$$

$$d_1 = 0.004a \sqrt{\frac{s_p}{n k_f l_f}}\,. \tag{18}$$

In order to solve equation (14), the Newton method of determining zero places of function has been used. Computational algorithm is shown in fig. 2. It allows us to determine efficiency Q_u of the water intake and analytical depression s for the assigned apparent depression s_p in the cumulative well, using the formulae of Surow, Razumow and Maciejewski completed with formulae (10) and (11).

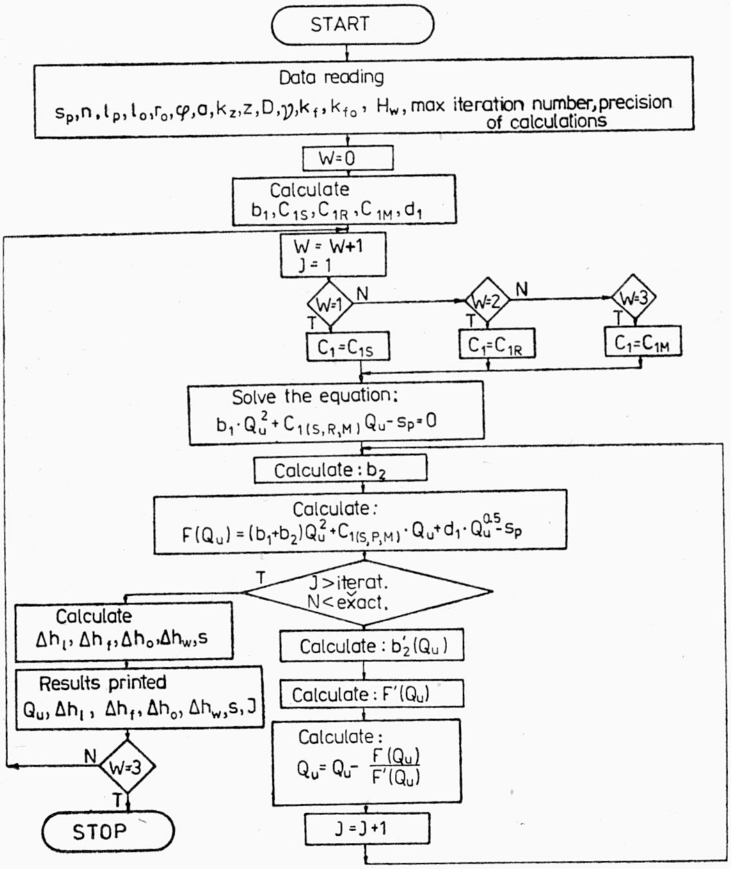

Fig. 2. Algorithm of the „DREN" program
Rys. 2. Algorytm programu „DREN"

The denotations used in algorithm are identical with those used in the text and letter indexes correspond to: S — the Surow formulae, R — the Razumow formulae, M — the Maciejewski formula, respectively.

Based on the algorithm (fig. 2), the "DREN" program in the Fortran language for a digital computer Odra 1300 has been formulated.

4. AN EXAMPLE OF THE "DREN" PROGRAM APPLICATION

In order to check the usefulness of the developed methods for determining the basic characteristic of the efficiency of infiltrating radiant water intakes, numerical calculations $s_p = f(Q_u)$ have been performed for testing data of the Warsaw radiant water intake "Gruba Kaśka".

Data: $H_w = 29.2$ m, $k_f = 3.5 \times 10^{-4}$m/s, $k_{f0} = 3.0 \times 10^{-4}$m/s, $\bar{l}_f = 79.1$ m, $\bar{l}_0 = 13.4$ m, $n = 15$ collectors, $r_0 = 0.147$ m, $\varphi = 32\,\%$, $z = 6.7$ m, $D = 13.8$m, $k_z = 1.0 \times 10^{-3}$ m, $a = 12.0$, $R = 1.0$ m, $\nu = 1.306 \times 10^{-6} m^2/s$, $s_p = 1.0$, 2.0, 3.0, 4.0, 5.0, 6.0, and 7.0 m. Results are shown in fig. 3.

Some results of field measurements of the efficiency of the Warsaw radiant water intake have been published in paper [17]. From July 21 till November 11, 1971, mean efficiency Q_u of the intake amounted to 1.435 m³/s at average apparent depression $s_p = 6.43$ m.

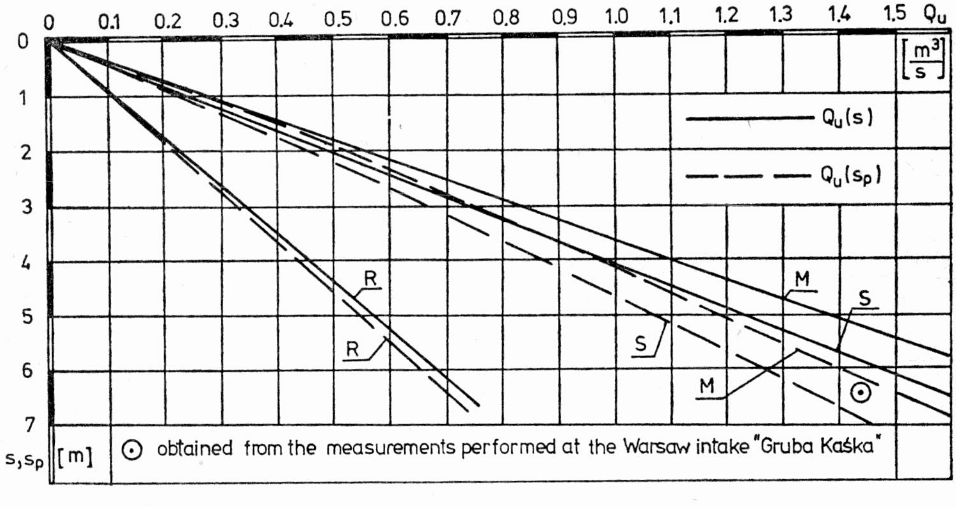

Fig. 3. Graphical interpretation of numerical calculations of the efficiency characteristic of the radiant intake in Warsaw

S — according to the Surow formula, M — according to the Maciejewski formula, R — according to the Razumow formula

Rys. 3. Graficzna interpretacja wyników obliczeń numerycznych charakterystyki wydajności ujęcia promienistego w Warszawie

S — według wzoru Surowa, M — według wzoru Maciejewskiego, R — według wzoru Razumowa

By applying the "DREN" program for $s_p = 6.43$ m, the following results have been obtained:

a) losses of energy Δh_s and $\Delta h_f (s_p = s)$ not included:
according to the Surow formula $Q_u = 1.590$ m^3/s,
according to the Maciejewski formula $Q_u = 1.760$ m^3/s,
according to the Razumow formula $Q_u = 0.755$ m^3/s;

b) losses of energy Δh_s and Δh_f included:
according to the Surow formula $Q_u = 1.350$m^3/s,
according to the Maciejewski formula $Q_u = 1.495$ m^3/s,
according to the Razumow formula $Q_u = 0.710$ m^3/s.

When hydraulic losses of the collectors were not taken into account, the discrepancies between the results of calculations according to the formulae of Surow, Maciejewski and Razumow and the results of pumpings are considerable, ranging from -47.4% to $+23\%$. If, however, these losses were included, the differences varied from ca -50% for the Razumow formula and -5.9% for the Surow formula to $+4.2\%$ for the Maciejewski formula. Thus, the formulae of Surow and Maciejewski, completed with the formulae (10) and (11), may be regarded as being appropriate for the conditions of the Warsaw intake.

The presented results of calculations and comparisons indicate a significant effect of hydraulic losses Δh_f and Δh_s on the efficiency of the infiltrating radiant intake. Under similar hydrogeological conditions this effect will be the higher the smaller the average diameter of the collectors and the greater their length [4], [13]. The calculated values should be compared with the results of field calculations made for this type water intakes.

5. CONCLUSIONS

The present paper allows us to draw the following conclusions:

1. If calculations of the efficiency of infiltrating radiant water intakes are based on the known to-day hydrogeological formulae and the loss of energy in the collectors is taken into account, then the results obtained are close to the measurement data. It must be stated, however, that basic differences between the results of calculations and measurements are not so much due to disregarding hydraulic losses in the collectors as to the application of not suitable hydrogeological formula in given conditions. In this case the data achieved may be successfully corrected by introducing losses Δh_s and Δh_f if the calculations were carried out according to suitably chosen formula.

2. The worked out hitherto formulae for calculation of hydrogeological infiltrating radiant water intakes are far from being perfect because of simplification as well as difficulties in analytical solution of this problem. Thus investi-

gations on physical models should be continued in order to describe in a more detailed way the phenomena accompanying the drawing of water from radiant intake and to give the adequate formula. Such investigations have been undertaken in the Institute of Environment Protection Engineering of the Technical University of Wrocław.

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OKREŚLANIE WYDAJNOŚCI PROMIENISTYCH UJĘĆ WODY Z UWZGLĘDNIENIEM STRAT ENERGETYCZNYCH W ZBIERACZACH

Przedstawiono metodę, która pozwala uwzględnić w obliczeniu podstawowej charakterystyki wydajności ujęć promienistych wody infiltracyjnej straty energetyczne powstające w zbieraczach. Zaprezentowano algorytm obliczeń numerycznych według metody Newtona. Na podstawie tego algorytmu opracowano program „DREN" w języku Fortran na maszynę cyfrową serii Odra 1300. Zamieszczono przykład zastosowania obliczeń $s_p = f(Q_u)$ dla określenia wydajności ujęcia promienistego w Warszawie. Stwierdzono, że uwzględnienie strat energetycznych w zbieraczach przy obliczaniu wydajności infiltracyjnych ujęć promienistych wody na podstawie wzorów Surowa i Maciejewskiego zbliża uzyskane rezultaty do rzeczywistych.

DIE BESTIMMUNG DER FILTERBRUNNENERGIEBIGKEIT MIT BERÜCKSICHTIGUNG VON ENERGIEVERLUST IN DEN ROHREN

In dem hier besprochenen Verfahren werden die in den Rohren entstandenen Energieverluste in die Berechnung der Filterbrunnenergiebigkeit miteingezogen. Der Algorithmus für die Computerberechnungen wird mit Hilfe der Newtonschen Methode aufgebaut. Dieser Algorithmus wird als Stützpunkt für die Bearbeitung des Programmes DREN in der Maschinensprache Fortran angewendet. Das hier besprochene Beispiel bezieht sich auf die Bestimmung der Ergiebigkeit eines Warschauer Filterbrunnens. In den Berechnungen werden die Surovschen und Maciejewskischen Formeln ausgenützt. Es wird festgestellt, daß die Berücksichtigung der in den Filterrohren entstandenen Energieverluste die Ergebnisse der so durchgeführten Berechnungen zu jenen der Wasserforderung annähern.

ОПРЕДЕЛЕНИЕ ПРОИЗВОДИТЕЛЬНОСТИ РАДИАЛЬНЫХ ВОДОЗАБОРОВ С УЧЁТОМ ЭНЕРГЕТИЧЕСКИХ ПОТЕРЬ В ВОДОСБОРНИКАХ

Предложен метод учёта энергетических потерь, возникающих в водосборниках, в расчёте основных параметров производительности радиальных водозаборов инфильтрационной воды. Представлен алгоритм численных расчётов по методу Ньютона, на основе которого разработана программа „Дрен" на языке ФОРТРАН для цифровой вычислительной машины ОДРА 1300. Приведён пример применения расчётов $s_p = f(Q_u)$ в определении производительности радиального водозабора в Варшаве. Отмечено, что учёт энергетических потерь в водосборниках при расчёте производительности радиальных инфильтрационных водозаборов на основе формул Суровау Мацеевского приближает полученные результаты к результатам нагнетаний.