Some effects of groundwater extraction in the western part of the Netherlands on the hydrological regime

G. J. Heij

Abstract. The increasing urbanization in the western part of the Netherlands has an increasing influence on the country’s groundwater regime. Through this there is found to be an ever stronger conflict between different parties interested in the groundwater. In order to weigh one interest against another, insight is needed into the effect of different activities on the groundwater head and flow and the consequences of such effects. An important activity in this area, inherent in the increasing urbanization, is groundwater extraction. Drawdown, as a result of groundwater extraction, amongst other things influences seepage or infiltration and settlement of semipervious layers, resulting in subsidence and an increase of the hydraulic resistance. The influence of another activity on the hydrological regime, the cutting of a canal, can make a considerable call on a groundwater reservoir. In view of the increasingly strong confrontation with other interests, intensive investigation is required into the most suitable locations for groundwater extraction. Extracted groundwater which is not consumed must be returned to the soil if possible. In addition to this, continuous attention should be given to other possibilities to satisfy the need of water.

1. INTRODUCTION

The increasing urbanization in the western part of the Netherlands has a growing influence on the groundwater regime. As the result of this one finds an ever stronger conflict between different parties interested in the groundwater. These interests mostly reduce to a certain requirement in respect of the hydraulic head or the groundwater table. In order to balance the different interests it is necessary, amongst other things to have a better insight into the effect of a certain activity by which the hydraulic head and the groundwater flow is influenced. One of the most important of the activities associated with increasing urbanization is groundwater extraction, permanent (such as for industries and public water supply), as well as temporary (dewatering of construction sites by means of well points). Activities on behalf of other interests are, for example, land reclamation projects, control of polder level and cutting of canals.
In this paper particular attention will be paid to the consequences of lowering the hydraulic head through the extraction of groundwater, whilst Broeze and Couwenhoven (1977) deal with the consequences of the lowering of the groundwater table.

The influence of the extraction of groundwater on deep groundwater flow may be calculated with formulae for radial-symmetrical flow.

To obtain an impression of the influence on the groundwater regime by cutting a canal we take as an example the cutting of the Amsterdam—Rijncanal, and then we examine some of the consequences of lowering the groundwater head by extraction, such as changes in seepage and infiltration and settlement of semipermeable layers. Finally attention will be given to the possibility of reducing or preventing these reductions of the groundwater head.

2. THE INFLUENCE ON THE HYDROLOGICAL REGIME BY THE CUTTING OF THE AMSTERDAM—RIJNCANAL

In this section attention will be paid to the influence on the hydrological regime of the Kromme Rijn area by cutting the part of the Amsterdam—Rijncanal between the railway bridge at Houten and Wijk bij Duurstede (Fig.1). The cutting of the Amsterdam—Rijncanal was started in 1943. To the end of 1950 the water level of the canal was maintained at NAP + 0.90 to 1.10 m. At this time the provincial highway now existing between Houten and Schalkwijk was functioning as a dam and had not yet been cut to allow a join-up of the two opposing sections of the canal. In December 1950 the level between Houten and Wijk bij Duurstede was purposely lowered to approximately NAP + 0.30 m and again in February 1951 to NAP — 0.40 m. This meant that finally the canal level was 1.50 m below the groundwater head that existed at that time.

It had already been arranged, during the cutting of the canal, to provide water for strips of land 400 m wide on each side of the canal.

FIGURE 1. Lowering of the hydraulic head caused by the cutting of the Amsterdam—Rijncanal. (Scale 1:15 000).
The lowering of the head, as a result of the cutting of the Amsterdam—Rijncanal is illustrated in Fig.1 (Committee for Hydrological Research Kromme Rijn area, 1968). The following calculation demonstrates that a considerable call is made on available groundwater in the areas through which the canal was cut; on the basis of this calculation an impression will be obtained of the quantity of groundwater which is drained-off by the canal over the length $AC$ in Fig.1.

For the greater part of western Netherlands the schematic hydrogeological conditions can be depicted by Fig.2. The resistance $c_2$ of the deep-lying semipervious layer is mostly greater than the resistance $c_1$ of the semipervious top layer. That is also probably the case in the area now under consideration. For the calculation in question it is therefore taken that $c_2$ is infinitely great. The groundwater head (with respect to the polder level) as the consequence of cutting a canal can be calculated from the formula:

$$
\psi_x = \varphi_0 \frac{\lambda_p B}{2\lambda_k^2 + \lambda_p B} e^{-x/\lambda_p}
$$

in which (Fig.3):

- $\psi_x$ = groundwater head in respect of the polder level [m];
- $\varphi_0$ = difference between polder level and canal level [m];
- $B$ = width of the canal [m];
- $\lambda_p = \sqrt{kDc_p}$ = leakage factor caused by the semipervious top layer of the bordering polders [m];
- $\lambda_k = \sqrt{kDc_k}$ = leakage factor caused by the clay layer remaining under the canal bed or caused by a mud layer existing on the canal bed [m];
- $kD$ = transmissivity of the first aquifer [m$^2$/day];
- $x$ = horizontal distance in relation to the canal side [m].

This formula can be derived from the following formula (Bruggeman, 1970):

$$
\varphi_x = \varphi_0 \left( 1 - \frac{\lambda_p \sinh \frac{B}{2\lambda_k} e^{-x/\lambda_p}}{\lambda_k \cosh \frac{B}{2\lambda_k} + \lambda_p \sinh \frac{B}{2\lambda_k}} \right)
$$
with the approximation

$$\tanh \frac{B}{2\lambda_k} = \frac{B}{2\lambda_k}$$

This allows for $B < \lambda_k$, which generally holds good for Dutch circumstances.

In the case of the pattern of lowering illustrated in Fig. 1, the factor

$$\varphi_0 = \frac{\lambda_p B}{2\lambda_k^2 + \lambda_p B}$$

can be calculated with the aid of formula (1). Here, this amounts to approximately 1.2 m (calculated from the line of lowering of 0.80 m).

The rate of flow can now be calculated from

$$q = \varphi_0 \frac{\lambda_p B}{2\lambda_k^2 + \lambda_p B} \frac{kD}{\lambda_p}$$

(2)

which is obtained through differentiating (1). In (2) $q$ is the drained rate of flow in cubic metres per linear metre per day. For the portion $AB$ of the canal $\lambda_p$ = approx. 1300 m can be maintained, and for the length $BC$, $\lambda_p$ is equal to approx. 1650 m.

These values originate from seepage calculations made by the National Institute for Water Supply along the Amsterdam–Rijncanal. For $kD$ 2000 m$^2$/day can be utilized. This is an average value deduced from several pumping and well tests carried out along the canal. It is possible to calculate the total quantity of groundwater drained off, $Q$, for a certain distance $L$, by the formula:

$$Q = 2\varphi_0 L \cdot \frac{\lambda_p B}{2\lambda_k^2 + \lambda_p B} \frac{kD}{\lambda_p}$$

(3)
Taking for
\[
\frac{\varphi_0 \lambda_p B}{2\lambda_k^2 + \lambda_p B}
\]
the earlier calculated value 1.2, one can roughly calculate the quantity of drained groundwater for the part of the canal under consideration (Table 1). This comes to approx. 3.5 m$^3$ m$^{-1}$ day$^{-1}$, averaged over the complete canal, which amounts to approx. 11 000 000 m$^3$ per year. Should this be a groundwater extraction for water supply, one may say that this is a very considerable extraction for Dutch conditions.

3. INFLUENCING SEEPAGE OR INFILTRATION

As one of the consequences of lowering the groundwater head, reduction of seepage or increase of infiltration, or a change from seepage to infiltration can occur. The model investigation carried out by the National Institute for Water Supply for the Eiland van Dordrecht (Meinardi and Heij, 1977) gives an impression of the order of magnitude of these changes in the Dutch polder areas as a result of groundwater extraction. In this investigation the subsoil is represented by considering the semipermeable layer 2 (see Fig.2) to be impermeable. The investigation was directed to the relation between flow and chemical composition of the groundwater. Through insufficient data concerning the groundwater potentials in aquifer 1, using geological, agricultural (data concerning the groundwater table) and hydrographical data and calculated and estimated hydraulic characteristics, a hydrogeological model was conceived (steady state flow) based on the finite element method. With this the extent of the groundwater flow as well as its direction is determined. The model offers the opportunity of evaluating the situation without groundwater extraction.

The orders of magnitude of the input data are as follows:

- polder level: mostly NAP – 1.00 to –1.50 m;
- mean evaluation of the tide: NAP + 0.30 to + 0.50 m;
- $kD = 400$ to $700$ m$^2$/day;
- $c = 500$ to 2000 days;
- $c_r = 150$ to 200 days in the north, reducing to 10 to 20 days in the south.

The thickness of the aquifer amounts to 7.5 to 10 m, and the thickness of the semipermeable top layer (clay and peat) is from 7.5 to 15 m. The location and magnitude of the input data relative to extraction (well point systems and groundwater extraction for water supply) in addition to the consequences thereof on the groundwater regime are shown in Figs. 4, 5 and 6.

It is to be noted, that extraction by the town of Dordrecht has caused a change from seepage to infiltration over a considerable area and that the infiltration from the River Merwede has increased considerably.
FIGURE 4. Computed groundwater potentials, (a) without extraction and (b) with extraction. (Scale 1:125 000).
FIGURE 5. Computed seepage or infiltration, (a) without extraction and (b) with extraction. (Scale 1:125 000).
FIGURE 6. River infiltration, (a) without extraction and (b) with extraction [mm/day]. (Scale: 1:125 000).
4. SETTLEMENT OF SEMIPERVIOUS LAYERS

Due to lowering of the groundwater head in an aquifer bounded by semipervious layers, these layers will settle, and as they hold a greater content of compressible material (peat) and as they are thicker, this settlement will be greater. The ratio between the new and original effective stresses in the semipermeable layers also plays a role. As the result of this settlement slowly being effected, land subsidence will occur.

There is also the possibility existing that the hydraulic resistance of the semipervious layers will increase. These two points will be gone into further from the aspect of groundwater extraction.

4.1. Land subsidence

Through land subsidence, subsidence of buildings will occur. Damage to buildings will not, however, occur generally through subsidence, but through differences in the degree of subsidence, which can arise through differences in drawdown over short distances. These differences will occur close to the extraction point or through inhomogeneity of the subsoil. Damage can also occur as a consequence of drawdown arising through uneven loading being applied to a building, which is associated with its particular structure. Above all other considerations, this can occur to buildings having cellars which occupy less surface area than the building itself. Lowering of the groundwater table can have the effect of negative skin friction applied to the cellar walls associated with a greater loading of the piles supporting these cellar walls, and with the chance of breakage of the piles so that cracks occur in the walls. It is thus of importance that the conditions of the foundations of buildings within the area influenced and the loads of the supporting piles are determined before any groundwater extraction in the area is begun which could influence the groundwater table, with the aim of determining the possible damage caused by the extraction. If the loading condition is critical prior to extraction, then only a slight lowering of the groundwater table is sufficient to cause damage.

4.2. Increase of the hydraulic resistance

Through settlement of a semipermeable layer caused by groundwater extraction the permeability of the layer will decrease and thus the hydraulic resistance will increase. The shallower and thicker the layer the greater the degree of settlement, and thus also probably the increase in the hydraulic resistance (the c-value). In the case of deep layers where a very strong settlement has already occurred, an increase of the effective stresses will then have a smaller effect. In the following, a method is proposed of obtaining a general impression of the order of magnitude of the increase in the resistance as a result of groundwater extraction. In this case the time factor (the delay between a change in the stress in the layer and the settlement) is ignored. We will only consider the initial and final conditions, taking into consideration a prolonged extraction.

The average hydraulic resistance of a homogeneous semipermeable layer is approximated by the formula (Heij, 1977):

\[
c = H \int_0^d \sigma_{kx} \, dx\]

where

\[
H = \text{a proportionality factor} \, \text{[day/m}^2\text{]}, \text{determined by the nature of the semipervious layer};
\]
\( \sigma_{kx} \) = the effective stress at a depth of \( x \) m beneath the upper surface of the semipervious layer [tonnes/m\(^2\)];

\( d \) = thickness of the semipervious layer [m].

In the case where the semipervious layer lies adjacent to the ground surface (Fig.2), the following formula holds good, with the groundwater table at the surface (\( h_1 \) and \( h \) are equal to zero, Fig.7)

\[
\sigma_{kx} = \frac{x}{d} (d \gamma_n - d \gamma_w - \Delta \varphi \gamma_w)
\]

in which

\( \gamma_n \) = specific saturated mass [tonnes/m\(^3\)];

\( \gamma_w \) = specific mass of water [tonnes/m\(^3\)]

Inserted in (4) this gives

\[
c = Hd \left( \frac{d - \Delta \varphi}{2} \right)
\]

in which we take \( \gamma_n = 2 \) tonnes/m\(^3\) and \( \gamma_w = 1 \) tonne/m\(^3\).

It is now found, as the result of groundwater extraction, that a lowering of the head \( \varphi \) takes place under the semipermeable layer, the following formula holds good for the new value of \( c \) which is finally found if the process of settlement is terminated:

\[
c = Hd \left( \frac{d - \Delta \varphi + \varphi}{2} \right)
\]

The increase in the value \( c \) thus amounts to a factor

\[
\frac{d - \Delta \varphi + \varphi}{d - \Delta \varphi}
\]

This factor serves as a very general approximation.
As an example, the groundwater extraction which is carried out by Dordrecht borough on the Eiland van Dordrecht is given (see Figs. 4, 5, 6). According to data supplied by Dordrecht the present-day drawdown at the pumping station amounts to 3 to 4 m. The thickness of the Holocene clay and peat layers amounts to approx. 10 m. Without knowing exactly the difference in head over the top layer of clay before the extraction (it is difficult to reproduce the groundwater table before extraction) it is possible to calculate, with the former quoted factor of increase, that as a result of the extraction the increase in the value of $c$ has amounted to approx. 1.5. In the model representing the Eiland van Dordrecht, the value of $c$ fed in for the pumping station is 2000 days. The $c$-value for the surrounding area amounts to approx. 1500 days. An increase in the value of $c$ causes a greater lowering of the head in the aquifer, subject to groundwater extraction than that calculated for the original value of $c$. In the case that there still exists an aquifer above the semipermeable layer, the final drawdown in that aquifer will be less than in the case of using the original value for $c$.

5. LIMITING THE INFLUENCE OF GROUNDWATER EXTRACTION ON THE HYDROLOGICAL REGIME

Beginning from the standpoint that to meet the need for drinking water and water for industrial use it is still necessary to extract groundwater in the Netherlands, it could be proposed that due to the fact that there are conflicting interests concerned with groundwater, there is a need for intensive research into the most suitable locations for groundwater extraction. The local and regional influences of the extraction on the hydrological regime have to be assessed as accurately as possible.

Preferably the extraction of groundwater must take place from under the second semipermeable layer (Fig. 2). If, through quality considerations, this is found not to be desirable in connection with the presence of salt groundwater, then it is required that the groundwater extraction points are located as near as possible to a river, in order to limit the lowering of the head as much as possible. This is known as induced recharge (Maas, 1977). A number of investigations of a regional character are being carried out in the Netherlands, with the aim of determining the quantity of groundwater which can be extracted in a certain region, taking into account all interests concerned with groundwater.

If the extracted groundwater is not consumed (for example in the case of industrial cooling or drainage of construction sites), then it is desirable to return the water to the soil. This is already carried out in many towns.

Here too a decision can be made from the viewpoint of groundwater management as well as the prevention of undesirable lowerings. In every case a practical test is needed to determine whether there are any problems to be expected, for example clogging as the result of mixing two sorts of groundwater of different chemical compositions. In general the return of extracted groundwater to the soil can be effected without many problems in the case of anaerobic groundwater, under a top layer of clay or peat. From a viewpoint of compensation of drawdown the design of a return well system (the number, location and capacity of the wells) should be effected with care, otherwise the effect of uneven subsidence (see section 4) will be increased.

A problem arising, is the increase of the groundwater temperature by the return of water to the soil used for industrial cooling purposes. Here also each case should be investigated separately to determine whether such a return is technically possible and if there is a possibility that damage will result to other interests.

In the evaluation of the effects of an initiated groundwater extraction project, data on groundwater heads are an absolute necessity. Beside taking the necessary care in making a choice of extraction locations, attention has to be paid to the possibilities of meeting the need for water for drinking and industrial purposes by methods which
have little or no influence on the hydrological regime, for example the use of surface water, whether or not mixed with groundwater. In this case, however, the quality aspect plays a great role. Finally, a more critical attitude is required relative to the need for and the direct or indirect use of groundwater. As an example, dropping the use of groundwater for industrial cooling purposes is mentioned here and the coordination of water management and water supply projects.

REFERENCES


Committee for Hydrological Research Kromme Rijn area (1968) Report of the hydrological research in the Kromme Rijn area (in Dutch).

