Nordic Hydrology 4, 1973, 28–40
Published by Munksgaard, Copenhagen, Denmark

GROUNDWATER DEVELOPMENT AND ITS INFLUENCE ON THE WATER BALANCE

EGGERT HANSEN and SV. AAGE ANDERSSON

Technical University of Denmark, Copenhagen

Lowering the head of an artesian aquifer in Zealand, Denmark by pumping of groundwater is shown to affect the water balance.
Based on known amounts of groundwater being developed, the coefficient of transmissivity was determined and in combination with piezometric maps the net outflow of groundwater was computed for the pre-pumping period as well as for the pumping period.
The annual streamflow was found to decrease considerably and the groundwater recharge to increase by the same amount.

In Denmark approximately 99 % of the water supply is based on groundwater. In a recent investigation of Danish water resources for planning purposes (1) it is assumed for several regions that 50–70 % of the net rainfall (i.e. rainfall diminished by evapotranspiration) may be developed. These assumptions are based solely on technical-economic considerations. However, how are such extensive developments going to influence the water balance in the individual regions, and do they have any ecological effect? In this paper the first of these questions will be treated with special reference to a small watershed in the north-eastern part of Zealand where there are extensive groundwater developments for the water supply of Copenhagen. A couple of other small watersheds in the same region have earlier been investigated similarly by Lyshede (2), (3). However, by taking account of subterranean fluxes of water the present study differs from the previous ones.

The basin

The Græse å (Græse brook) basin is situated approximately 35 km north-west of Copenhagen and covers an area of 25 km². The location of the basin and the topographical water divides are shown in Fig. 1. Geologically, the area is rather homogeneous (4). The upper strata consist of glacial and later formations (quarternary deposits): mainly clay, sand, gravel and pebbles, while the pre-quarternary substrata of the entire area consist of limestone formations. A typical geological section adopted from (4) is shown in Fig. 2. The groundwater is taken in the very pervious upper strata (i.e. approx. 10 m below the surface) of the limestone, which is full of cracks and fissures due to the action of the glacial ice.

Hydraulically it is possible that the lower glacial deposits, consisting of sand and pebbles, and the upper zone of the limestone work together as a whole as one artesian aquifer.

Based on available hydrological data for the period 1946–1967, it is the purpose of this paper to evaluate the influence of a groundwater development started in 1955 on the water balance of the Græse å basin. Thus, in the following we shall compare the water balance of this basin for two different periods, viz. 1946–1955 and 1955–1967, which are characterized by no pumping and pumping, respectively.

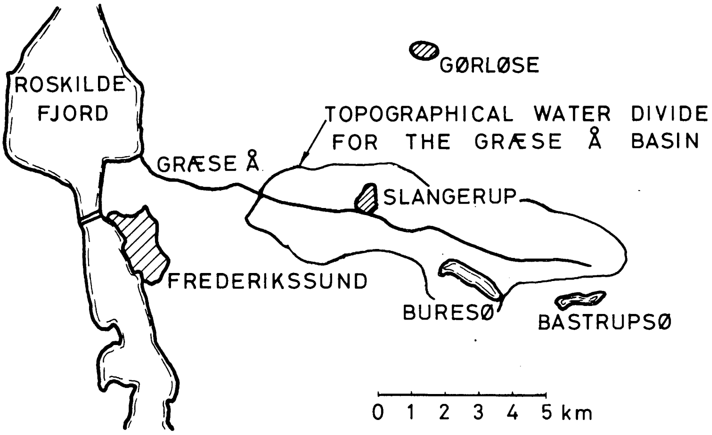

Fig. 1.

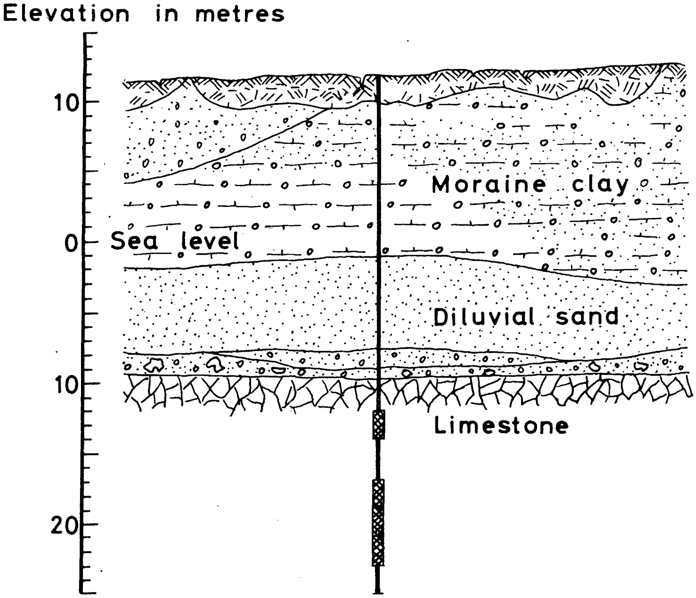

Fig. 2.

Water balance

For the region considered, the water balance may be expressed by

$$N = E + A_0 + A_u + Q + \Delta R \tag{1}$$

where

N = precipitation.
E = evapotranspiration.
A_0 = surface runoff leaving the region as stream flow.
A_u = subterranean flow leaving the region mainly as an artesian groundwater flow in the upper zone of the limestone formation.
Q = groundwater developed for water supply and exported from the region.
ΔR = change in the amount of water stored within the region and within the time interval considered.

As the time interval considered is one year, the quantities mentioned above are measured in the same units, namely mm/year.

Choosing the time interval from June 1 to May 31 makes it possible to assume $\Delta R \equiv 0$, as the soil water content at that time of the year is always negligible, and as there is no reason to believe that larger changes will occur from one year to another in the water content of the remaining part of the aerated zone as well as the groundwater reservoir.

For the years 1946–1960 the relevant data for precipitation and stream flow are obtained from the publications of the Danish Heath Society (5). For the rest of the years, viz. 1960–1967, the runoff data are obtained from the Water Supply Department of Copenhagen, while the rainfall data are based on the precipitation at a nearby meteorological station at Gørløse. In order to test the homogeneity of the resulting series of annual rainfall for the Græse å basin a double mass diagram was constructed relating the cumulative total of annual rainfall for the Græse å basin to the cumulative total of the corresponding annual rainfall for the entire county of Frederiksborg. As seen from Fig. 3, there are no indications of significant inhomogeneities in the rainfall data. Data on the quantities of water developed and the groundwater levels in the limestone were obtained from the Water Supply Department of Copenhagen.

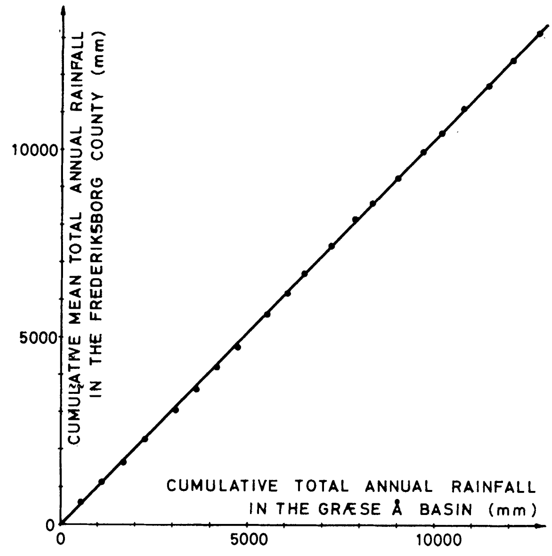

Fig. 3.

It is assumed that the net outflow of groundwater from the region is due exclusively to the flow in the previously defined artesian aquifer consisting of the pervious upper zone of the limestone and the lower glacial deposits. Thus we disregard any net outflow of water from the region due to interflow as well as groundwater flow in the upper glacial formations consisting mainly of moraine clay. The interflow will only rarely cross the topographical water divides, whereas the transmissivity of the upper glacial deposits is found insignificant as compared to the transmissivity of the artesian aquifer. Furthermore, we assume that the change in the net outflow of groundwater from one year to another is negligible within each of the periods characterized by no pumping and pumping, respectively. Thus we assume A_u constant for each of the periods 1946–1955 and 1955–1967.

Fig. 4 is a map of the mean groundwater level (piezometric head) in the upper zone of the limestone formations for the period unaffected by the groundwater development, i.e. 1946–1955. The map has been prepared on the basis of monthly observations of the groundwater level in approximately 30 observation wells. The corresponding map of the mean groundwater levels for the period of extensive groundwater development, i.e. 1955–1967, is shown in Fig. 5. The map shows that due to the pumping, several of the equipotential lines for the groundwater change into closed curves surrounding the pumping wells.

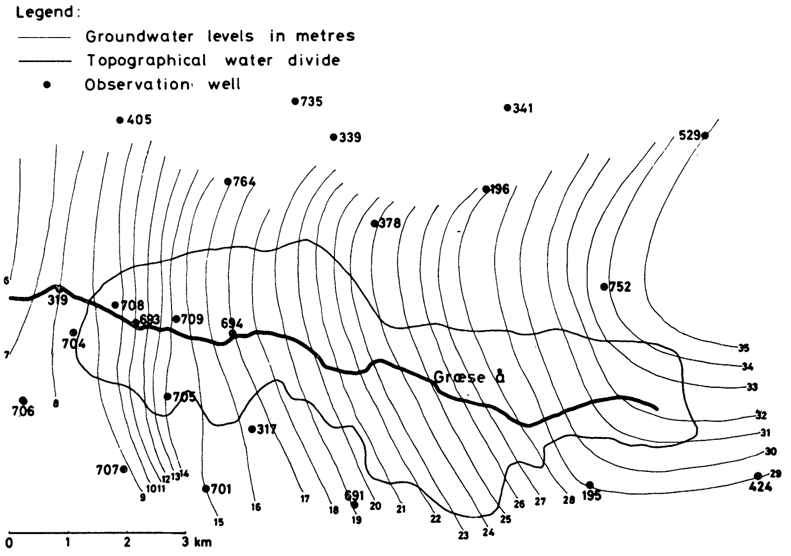

Fig. 4.

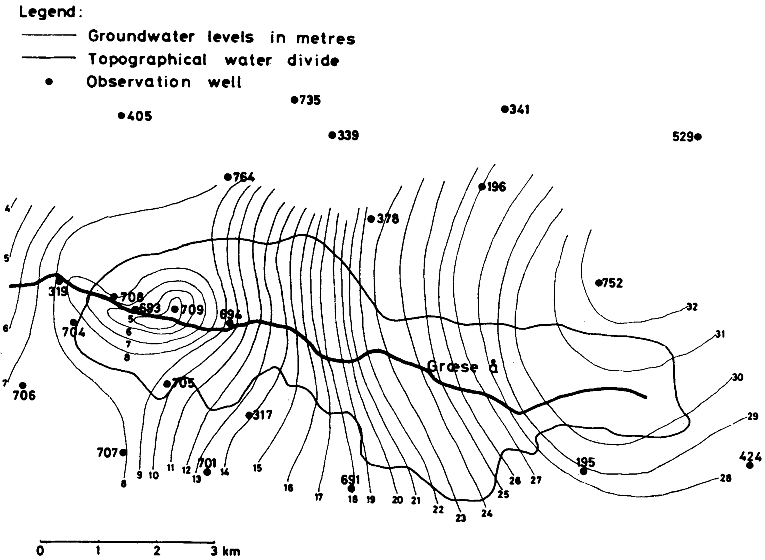

Fig. 5.

In order to obtain an estimate of the net flux of groundwater we assume that the aquifer is sufficiently spatially homogeneous to allow us to use a constant coefficient of transmissivity $T = k \cdot D$, k being the permeability and D the thickness of the aquifer. Thus denoting the piezometric head (pressure head) in the aquifer by h, we obtain from Darcy's law the flux vector $\vec{q}$ (m^2/s) for the groundwater flow.

$$\vec{q} = T \text{ grad } h \tag{2}$$

Of course, $h(x,y)$ and $\vec{q}(x,y)$ may be functions of the horizontal coordinates x and y.

Denoting by L the horizontal projection of the topographical water divides surrounding the region considered (see Figs. 4 and 5), we obtain the net outflow of groundwater A_u from the area as follows

$$A_u = \frac{1}{A} \int_L T \text{ grad } h \cdot \vec{dx} \tag{3}$$

A being the area of the Græse å basin.

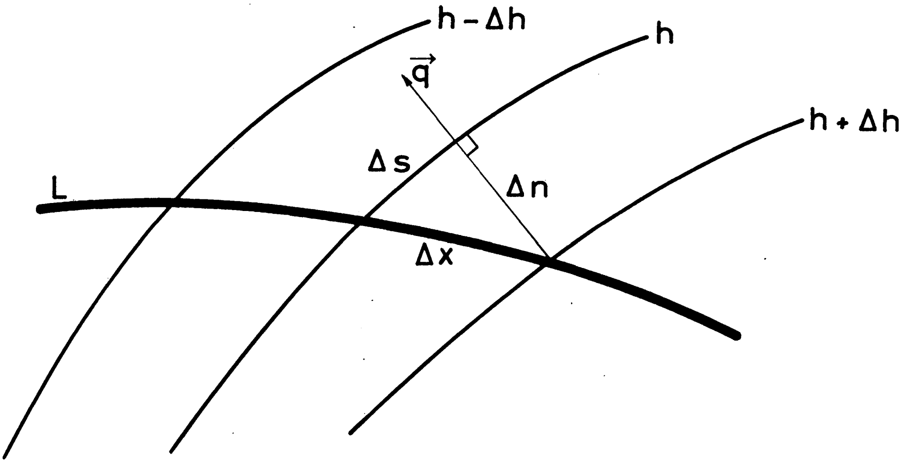

Fig. 6.

As h(x,y) is known from Figs. 4 and 5, only a numerical value for T is missing in order to make it possible to calculate A_u by the following discrete version of Eq. (3).

$$A_u = \frac{T}{A} \sum_{L} \frac{\Delta h}{\Delta n} \Delta s = \frac{T\,\Delta h}{A} \sum_{L} \frac{\Delta s}{\Delta n} \tag{4}$$

The equidistance Δh between the potential lines is assumed constant, and in the present investigation we use $\Delta h = 1$ metre. Considering an element Δx of the limiting boundary L, Δn denotes the projection of Δx in the direction of flow, while Δs is the projection of Δx in the direction normal to the flow (see Fig. 6).

Using Eq. (4) with L being one of the closed potential lines surrounding the pumping wells (see Fig. 5) we have obtained a means of calculating the coefficient of transmissivity T of the aquifer, because in this situation $A_u = \overline{Q}$, where $\overline{Q}$ denotes the mean annual discharge of the pumping wells for the period 1955–1967. From Table 1 we find that $\overline{Q} = 142$ mm/year. By this procedure we get the following mean value of $T = 86500$ m^2/year $= 2.76 \times 10^{-2}$ m^2/s.

From the groundwater maps in Figs. 4 and 5 in combination with Eq. (4) we now obtain the net outflows of groundwater from the Græse å basin, namely

$A_u = 35$ mm/year for the period before the start of the pumping and $A_u = -23$ mm/year for the period with pumping.

These figures are of great interest for the evaluation of the influence of groundwater development on the amount of water infiltrating to the groundwater, that is the groundwater recharge. For the period before pumping we found that the yearly mean of natural infiltration (recharge) was approximately 35 mm. The above figures show, however, that due to pumping the yearly mean of infiltration has increased to approximately $142 - 23 = 119$ mm. Thus the decrease of the piezometric head in the aquifer resulting from the pumping has increased the infiltration by approximately a factor of three.

Based on the calculations of A_u and the measurements of N, A_0, and Q, we are able to derive the evapotranspiration $E = N-(A_0 + A_u + Q)$ and the net rainfall $N-E = A_0 + A_u + Q$ (see Table 1 and Fig. 7).

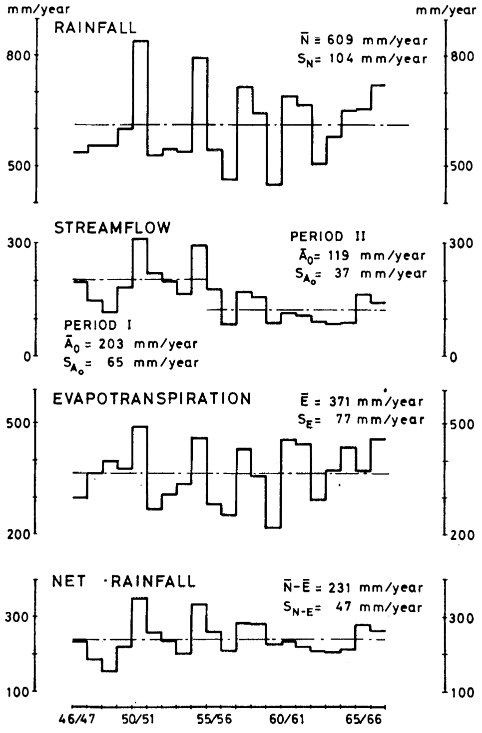

Fig. 7.

Table 1.

Period	Year	Rainfall N (mm/year)	Surface runoff A_0 (mm/year)	Groundwater runoff A_u (mm/year)	Developed groundwater Q (mm/year)	Evapotrans-piration E = $N-(A_0+A_u+Q)$ (mm/year)	Net rainfall N–E = A_0+A_u+Q (mm/year)
Without pumping (Period I)	51/52	537	195	35	0	307	230
	52/53	555	145			375	180
	53/54	554	111			408	146
	54/55	600	181			384	216
	46/47	841	315			491	350
	47/48	529	220			274	255
	48/49	546	196			315	231
	49/50	539	160			344	195
	50/51	795	298			462	333
Means (Period I)		611	203	35	0	373	238
Pumping (Period II)	55/56	544	176	–23	105	286	258
	56/57	465	79		147	262	203
	57/58	717	170		135	435	282
	58/59	642	154		150	361	281
	59/60	450	82		164	227	223
	60/61	690	111		141	461	229
	61/62	667	104		136	450	217
	62/63	505	86		139	303	202
	63/64	579	80		141	381	198
	64/65	650	83		148	442	208
	65/66	654	161		140	376	278
	66/67	722	141		142	462	260
Means (Period II)		607	119	–23	142	369	238

As will be seen from Fig. 7, and as found by statistical analysis, there are no signs of the development of groundwater having influenced the evapotranspiration E. Under the prevailing conditions this was not to be expected either. As is true for the rainfall, we find that the evapotranspiration E may be regarded as an uncorrelated series having serial-correlation coefficients that differ only insignificantly from zero. N and E are approximately normally distributed, having standard deviations as shown in Fig. 7.

Considering the stream flow we realize that the average runoff has decreased from 203 mm/year to 119 mm/year due to groundwater pumping. The distribution of the mean monthly runoff for the two periods, as shown in Fig. 8, indicates that the decrease in runoff is distributed over the whole year, giving rise to a marked increase in the length of the period of low flows. In order to further clarify how the stream flow is influenced by the groundwater development the series of yearly minimum flows for the whole period under investigation is shown in Fig. 9, from which it will be seen that the average yearly minimum runoff has decreased from 2.0 l/s/km^2 to 0.8 l/s/km^2, corresponding to a factor of 0.4.

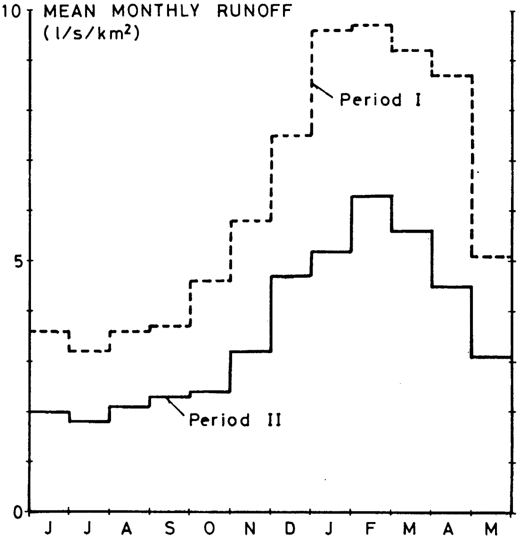

Fig. 8.

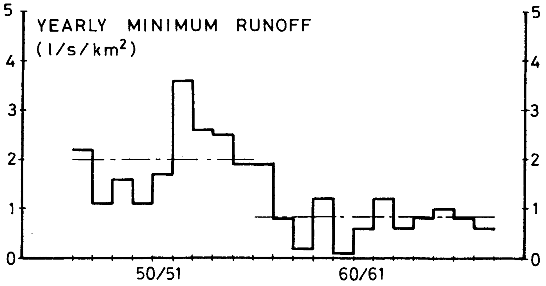

Fig. 9.

By means of Eq. (1) we may get an independent check on the findings related to the change in infiltration between the two periods. Denoting averaging by a bar, we find for the two periods that the change in the mean infiltration, i.e. in the average value of $A_u + Q$, may be expressed as follows

$$\Delta(\bar{A}_u + \bar{Q}) = \Delta(\bar{N}-\bar{E}-\bar{A}_0) \tag{5}$$

Thus, for the two periods considered, a change in the mean infiltration must be balanced by an equal change in the average value of net rainfall diminished by surface runoff. On the right-hand side of Eq. (5) $\Delta\bar{E}$ is the only quantity not directly observed. Assuming the evapotranspiration E to be a stochastic variable related approximately linearly to the precipitation N, i.e. $E = bN + a$, we obtain by substitution in Eq. (5)

$$\Delta(\bar{A}_u + \bar{Q}) = (1-b)\,\Delta\bar{N}-\Delta\bar{A}_0 \tag{6}$$

b is the coefficient of regression of E on N. For the investigation at hand we find on the basis of the 21 years' observations that E is closely linearly related to N, corresponding to a correlation coefficient $r = 0.91$. The coefficient of regression is found to be $b = 0.67$. Thus, using the figures of Table 1 we get $\Delta(\bar{A}_u + \bar{Q}) = -0.33 \cdot 4 + 84 = 83$ mm/year. This means that on the basis of Eq. (1) we may conclude that the mean infiltration has increased by approximately 83 mm/year from the period without pumping to the period with pumping. Previously, direct numerical integration of the net outflow of groundwater yielded for the same quantity $119 - 35 = 84$ mm/year. The agreement is surprisingly good and gives reason for some confidence in the value $T = 2.76 \times 10^{-2}$ m^3/s for the coefficient of transmissivity as well as for the assumption of horizontal homogeneity with regard to the transmissibility of the aquifer.

CONCLUSIONS

By lowering the head in the artesian aquifer, a groundwater development is shown to influence the water balance of a basin considerably, especially by causing a decrease in the stream flow as a consequence of an increased infiltration. As shown in the present investigation, the decrease in stream flow causes a decrease in the yearly minimum runoff as well as a marked increase in the length of the periods of low flows. The evapotranspiration is found to be approximately 370 mm/year, uninfluenced by the groundwater development. This value is in nearly complete agreement with the value $\overline{E} = 365$ mm/year found to be valid for watersheds (2) close to the one considered in this study.

Based on the known amounts of groundwater developed in conjunction with an assumption of spatial homogeneity, the coefficient of transmissivity of the aquifer is found to be $T = 2.76 \times 10^{-2}$ m^2/s. Using this value of T in combination with maps of the mean groundwater level, the mean net outflow of groundwater A_u from the basin considered is found to be 35 mm/year and -23 mm/year for the period without and with pumping, respectively. As the mean of the annual discharge for the period with pumping is $\overline{Q} = 142$ mm/year, the annual infiltration, that is the groundwater recharge, is thus found to increase from the undisturbed value 35 mm/year to a higher value 119 mm/year, due to pumping.

ACKNOWLEDGMENTS

The writers are grateful to the Water Supply Department of Copenhagen for their kind cooperation.

REFERENCES

(1) Vandressource. Forureningsrådet – Sekretariatet. Publikation nr. 14. København 1971.

(2) Beretning fra vandbalanceudvalget. Akademiet for de tekniske Videnskaber. Beretning nr. 17. København 1952. (English summary.)

(3) Lyshede, J. M.: Hydrologic Studies of Danish Watercourses. Folio Geographica Danica. Tom VI. Copenhagen 1955.

(4) Beretning fra Københavns Vandforsyning. København 1943.

(5) Beretning om Det danske Hedeselskabs kulturtekniske afdelings hydrometriske undersøgelser 1946–60. (7., 8. og 9. beretning).

Address:

Institute of Hydrodynamics and Hydraulic Engineering,
Technical University of Denmark, Building 115,
DK-2800 Lyngby, Denmark.

Received 29 September 1972.