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A Distributed Groundwater/Surface Water Model for the Suså-Catchment

Part II – Simulations of Streamflow Depletions Due to Groundwater Abstraction

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A distributed physically based model of the entire land phase of the hydrological cycle has been developed for the Suså-area, covering about 1,000 km^2 of Zealand, Denmark. The model is described in part I of the paper, also presented in this volume. The model's ability to simulate the streamflow depletion caused by a groundwater abstraction from a confined aquifer, overlaid by Quaternary drift deposits, has been tested on historical streamflow data from the catchment of Køge Å. This catchment has been heavily influenced by a major groundwater abstraction started in 1964.

The physical mechanisms of streamflow depletion are discussed, and the effects of a groundwater abstraction on the recharge to the confined aquifer and on the streamflow are illustrated. General conclusions regarding streamflow depletion due to groundwater abstraction are made.

Introduction

A large part of the world's water supply is based on groundwater, the development of which has been intensified very much during the last decades, and probably will continue intensifying for the coming decades also. As the groundwater development from an area becomes considerable, compared to the entire water resources of the area, the effects of the groundwater abstraction on the hydrological cycle becomes important.

In catchments where the groundwater abstraction takes place from a confined aquifer, which is overlaid by Quaternary drift deposits, the abstraction will cause an increase in the recharge to the confined aquifer, and a resulting decrease in the streamflow. In this paper the physical mechanisms involved are discussed. How, and to which extent is the recharge increased? How is the seasonal variation of the resulting streamflow depletion?

The Suså-Area and the Model

With respect to the description of the Suså-area, as well as the distributed groundwater/surface water catchment model, the reader is referred to part I of the paper, (Refsgaard and Hansen 1982), also presented in this volume.

The Køge Å catchment is neighbouring the Suså catchment to NE and is situated within the area covered by the model, see Fig. 1 in part I.

Streamflow Depletion in Køge Å

The model's ability to simulate the streamflow depletion caused by a groundwater abstraction from a confined aquifer, has been tested on historical streamflow data from the catchment of Køge Å. This catchment has been heavily influenced by a comprehensive groundwater abstraction, started at the Regnemark Waterworks in 1964.

For the Køge Å catchment, streamflow simulations for a period both before and after the establishment of the groundwater abstraction are shown in part I of the paper (Refsgaard and Hansen 1982).

For more detailed analyses of the consequences of groundwater abstractions on the streamflow, simulations for periods in the 1970's have been carried out, both with the actual historical groundwater abstraction rates, and with the groundwater abstraction rate kept constant at the 1960 levels, i.e. without any abstraction to the Regnemark waterworks. Some of the simulation results are shown in Fig. 1, where all the streamflow values have been smoothed by a 15 days moving average filter, in order to remove the high frequencies, and thus to clarify the seasonal pattern.

As it is seen, the simulated streamflow assuming the actual groundwater abstraction, Q_{sim}, agrees reasonably well with the recorded streamflow, Q_{obs}. The periods with disagreements between Q_{sim} and Q_{obs} in January-February 1977 and in February-March 1978 are dominated by snow accumulation and snow melt, which is modelled by a very simple degree day approach. On the other hand, the

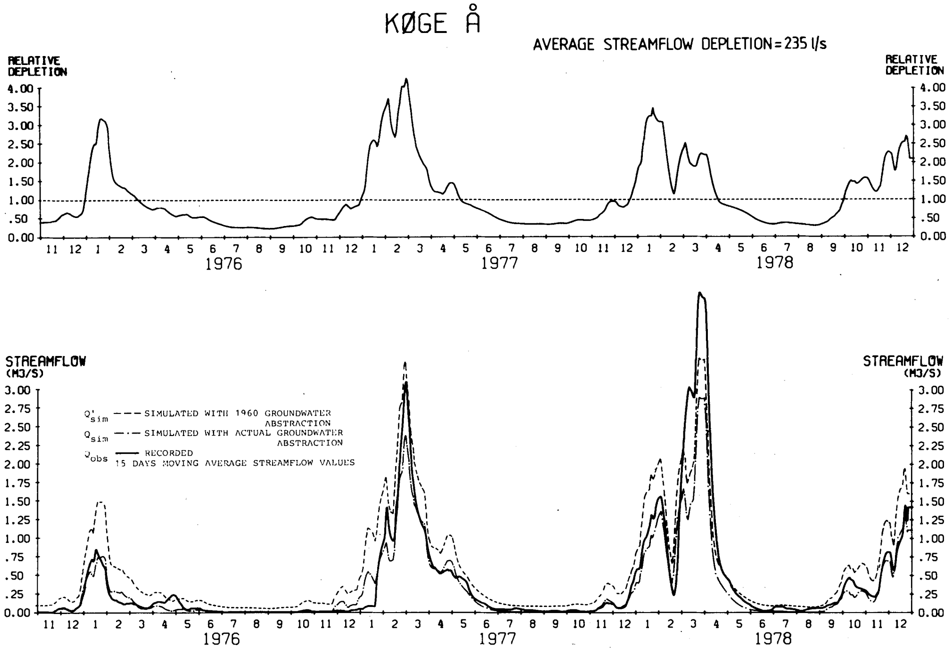

Fig. 1. Comparison of 15 days moving average streamflows for Køge Å 1976-78 (lower) and the relative streamflow depletion caused by the groundwater abstraction (upper).

simulated streamflow assuming the 1960 groundwater abstraction, Q^1_{sim}, is generally significantly higher than Q_{obs}. Q^1_{sim} is the streamflow, as it would have been expected to be, if the groundwater abstraction had not been increased since 1960. The difference $Q_{\mathrm{sim}} - Q^1_{\mathrm{sim}}$ is thus the streamflow depletion, caused by the increased groundwater abstraction.

As seen from Fig. 1, the difference between Q_{sim} and Q^1_{sim} is not constant, but seasonally dependent. The relative depletion shown in the upper half of the figure is the ratio between $Q_{\mathrm{sim}} - Q^1_{\mathrm{sim}}$ and the average of $Q_{\mathrm{sim}} - Q^1_{\mathrm{sim}}$ over the considered period. For example, the average streamflow depletion for Køge Å in the period 1976-78 is 235 l/s, cf. Fig. 1, while the relative depletion varies between 0.3 and 4.2 corresponding to an absolute depletion between 70 l/s and 1,000 l/s. Generally it is seen that the depletion is smallest in low flow periods and largest in high flow periods. Furthermore, it is noticed that the depletion is at its relatively largest at the beginning of the high flow period, cfr. the relative depletion compared with the streamflow values in Køge Å in the winter season 1977-78.

Finally, it can be noticed that the streamflow depletion in low flow periods equals the total streamflow, i.e. $Q_{\mathrm{sim}} = Q_{\mathrm{obs}} = 0$.

Physical Mechanisms

The reason for the seasonal streamflow depletion pattern can be explained by the following mechanisms:

a) A groundwater abstraction induces drawdowns of the hydraulic heads, H_l, of the confined aquifer.

b) The drawdowns in the confined aquifer increase the hydraulic gradient $(H_u-H_l)/L$ between the phreatic and confined aquifers having hydraulic heads H_u and H_l, respectively, and separated by an aquitard of thickness L. This change causes an increase of the average recharge from the phreatic aquifers.

c) A larger average recharge rate through the aquitard causes the phreatic water table to decline faster.

d) This means that the average elevation of the phreatic surface is lowered, relative to the natural and artificial drains responsible for a horizontal routing of water towards the streams in the phreatic aquifers. Thus, compared with the undisturbed situation, a smaller part of the water percolating out of the root zone into the phreatic aquifers will be diverted to the streams as drainflow and baseflow. In the model calculations these phenomena are accounted for, by means of two outlets in fixed elevations in the phreatic aquifers, simulating drainflow and baseflow respectively. (See Fig. 3 in part I). The decrease in streamflow equals of course the increase in groundwater recharge.

The mechanisms are illustrated in Fig. 2, where the consequences of a major groundwater abstraction on the hydraulic heads are shown, together with a relative streamflow depletion curve from the same area. The groundwater abstraction in question is a 21 million m^3/year abstraction from the central part of the Suså-catchment. It is described in more detail in Refsgaard and Stang (1981).

From Fig. 2 it is noticed that the recessions in hydraulic heads during the summer season are increased considerably as a consequence of the groundwater abstraction. For sub-polygon 32-3 (the second highest elevation - interval of polygon 32) this means that a larger volume of water must be replenished in the phreatic aquifer, before the horizontal water flow as baseflow and drainflow begins in the winter season. For instance, the lowest point of the water table in 1977 is 0.4 m below the lower outlet in the non-abstraction situation, but 3.2 m below in the abstraction situation. As the specific yield in polygon 32 is $S_Y = 0.01$ m/m, a recharge of 0.4 m × 0.01 m/m = 4 mm is necessary before the streamflow contribution begins from 32-3 in the non-abstraction situation, but of 3.2 m × 0.01 m/m = 32 mm in the abstraction situation.

Furthermore, it is seen that the condition of sub-polygon 32-1 has changed from a groundwater discharge situation (upward flow in the aquitard) to a recharge situation (downward flow in the aquitard). The consequence hereof is that there is no streamflow contributions from sub-polygon 32-1 in the low flow periods any longer.

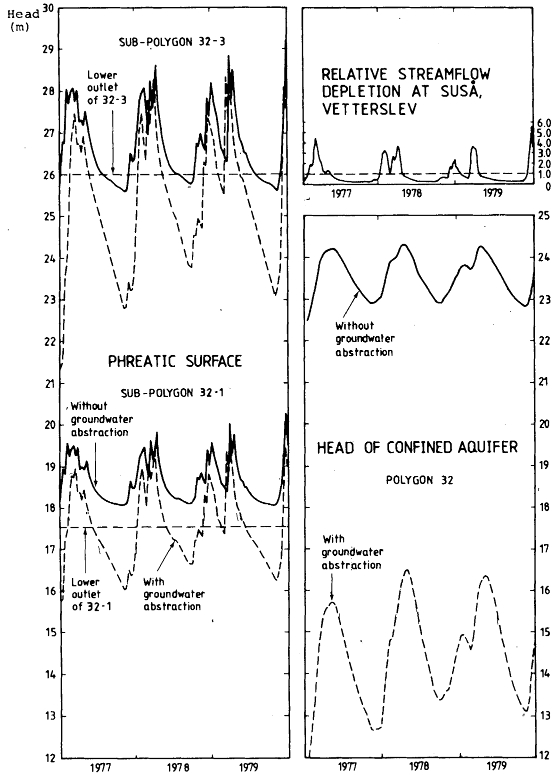

Fig. 2. A relative streamflow depletion curve together with the variations of hydraulic heads of the confined and two of the phreatic aquifers in polygon 32, both with and without a groundwater abstraction.

Table 1 – The water balance of the confined aquifer

	1953 (m^3/s)	1977 (m^3/s)	Change 53-77 (m^3/s)
Groundwater abstraction	0.176	0.830	+0.654
Leaking wells (Suså)	0.091	0.072	−0.019
Outflow across model boundaries	0.150	0.150	
Discharge to streams via the phreatic aquifers	0.445	0.178	−0.267
	0.862	1.230	
Total recharge	0.845	1.229	+0.384
Inflow across model boundaries	0.010	0.010	
	0.855	1.239	
Balance	0.007	−0.009	

Generally, the streamflow depletions from the groundwater discharge areas are more evenly distributed throughout the year than the streamflow depletions from the recharge areas.

Effect on Recharge and Streamflow

To illustrate some large scale consequences of the increased groundwater abstraction the water balances of the entire confined aquifer (940 km^2) are shown for the years 1953 and 1977 in Table 1. The deviations from zero are, apart from numerical uncertainties, caused by the non-steady situation. In 1953 the hydraulic heads decreased, due to an increase in groundwater abstraction. In 1977 the hydraulic heads increased, due to a decrease of the groundwater abstraction, and due to a larger recharge to the phreatic aquifers than in the preceding very dry year of 1976.

The recharge and discharge rates vary very few percent between wet years and dry years, if the groundwater abstraction is kept constant. It is noticed that the increase in groundwater abstraction is compensated for by an increase in the recharge (57%) and a decrease in the discharge to the streams (43%). As the increased recharge corresponds to a similar decrease of streamflow in the winter season, the streams are in fact deprived of the total volume of abstracted groundwater.

General Conclusions Regarding Streamflow Depletion Due to Groundwater Abstraction

In order to arrive at some general results and conclusions about streamflow depletion in catchments dominated by glacial drift the following three series of simulations have been carried out:

a) For six different subcatchments an additional groundwater abstraction of 25 mm/year evenly distributed throughout the individual catchments has been simulated. The six catchments from which the streamflow depletions have been calculated are the following:

- Vigersdal Å
- Køge Å
- Vedskølle Å
- Tryggevælde Å
- A high transmissivity area in the central part of the Suså-catchment
- A low transmissivity area near Glumsø

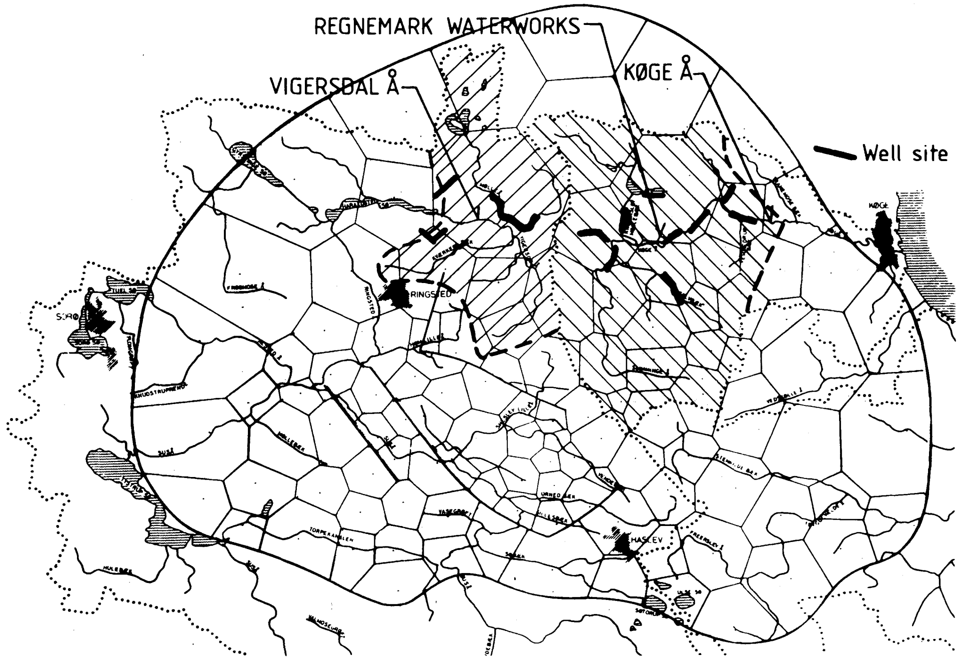

Fig. 3. The six catchments where the streamflow depletions caused by an additional 25 mm/year groundwater abstraction have been investigated.

The six catchments are shown in Fig. 3. The results for Vedskølle Å and Tryggevælde Å are shown in Fig. 4.

b) For the Køge Å catchment the consequences of different additional groundwater abstraction rates have been calculated. In Fig. 5 the streamflow depletions caused by a 10 mm/year and by a 200 mm/year additional groundwater abstraction are shown.

c) The importance of the location of the well site relative to the stream has been investigated in a high transmissivity area and in a low transmissitivity area.

All the simulations were carried out with the meteorological input data of 1975-80, but with the basic groundwater abstraction rates equal to the 1960-rates, i.e. a groundwater development stage corresponding to the one before the start of the Regnemark waterworks.

Re a): Six Differerent Catchments

As expected, the same general pattern is found for all six catchments, i.e. relative depletions smaller than 1.0 in the low-flow periods and larger than 1.0 in the high-flow periods.

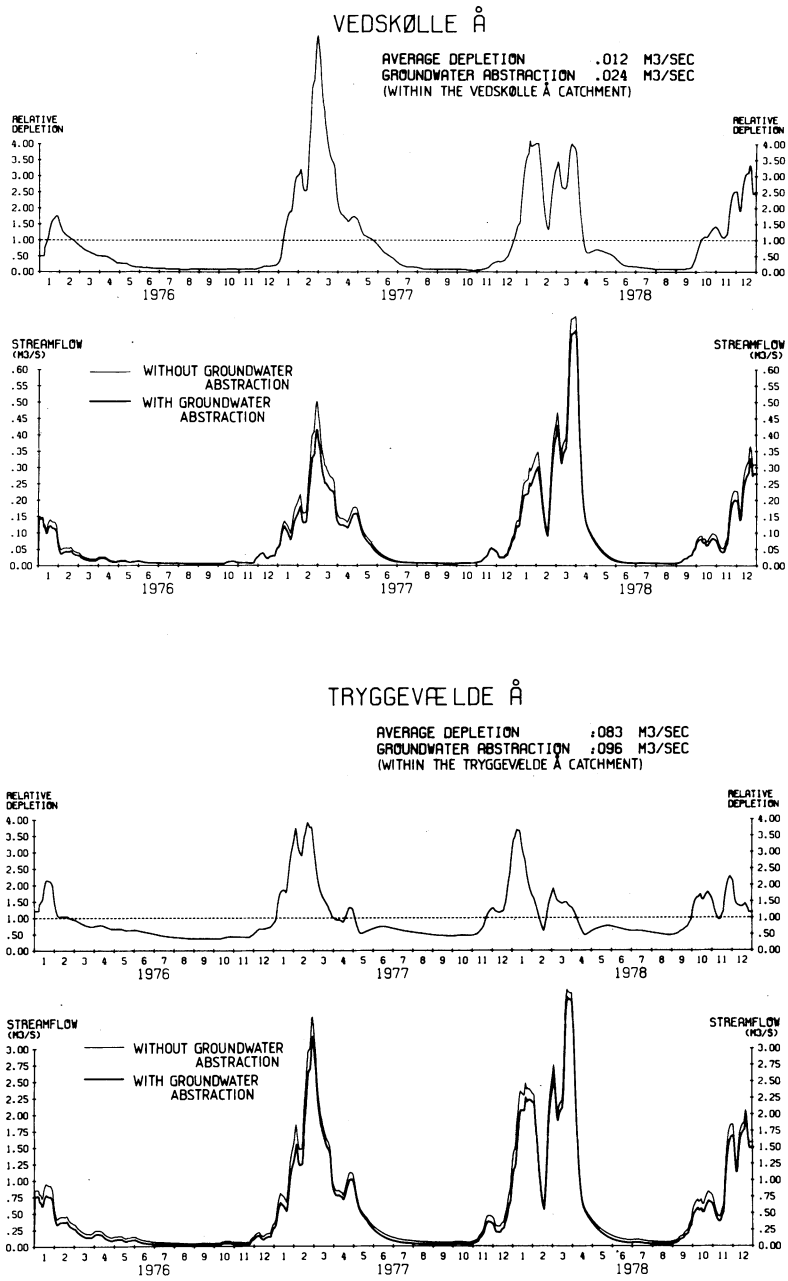

Fig. 4. Streamflow depletions caused by an additional 25 mm/year groundwater abstraction within Vedskølle Å and Tryggevælde Å catchments, respectively. All the streamflows are 15 days' moving average values.

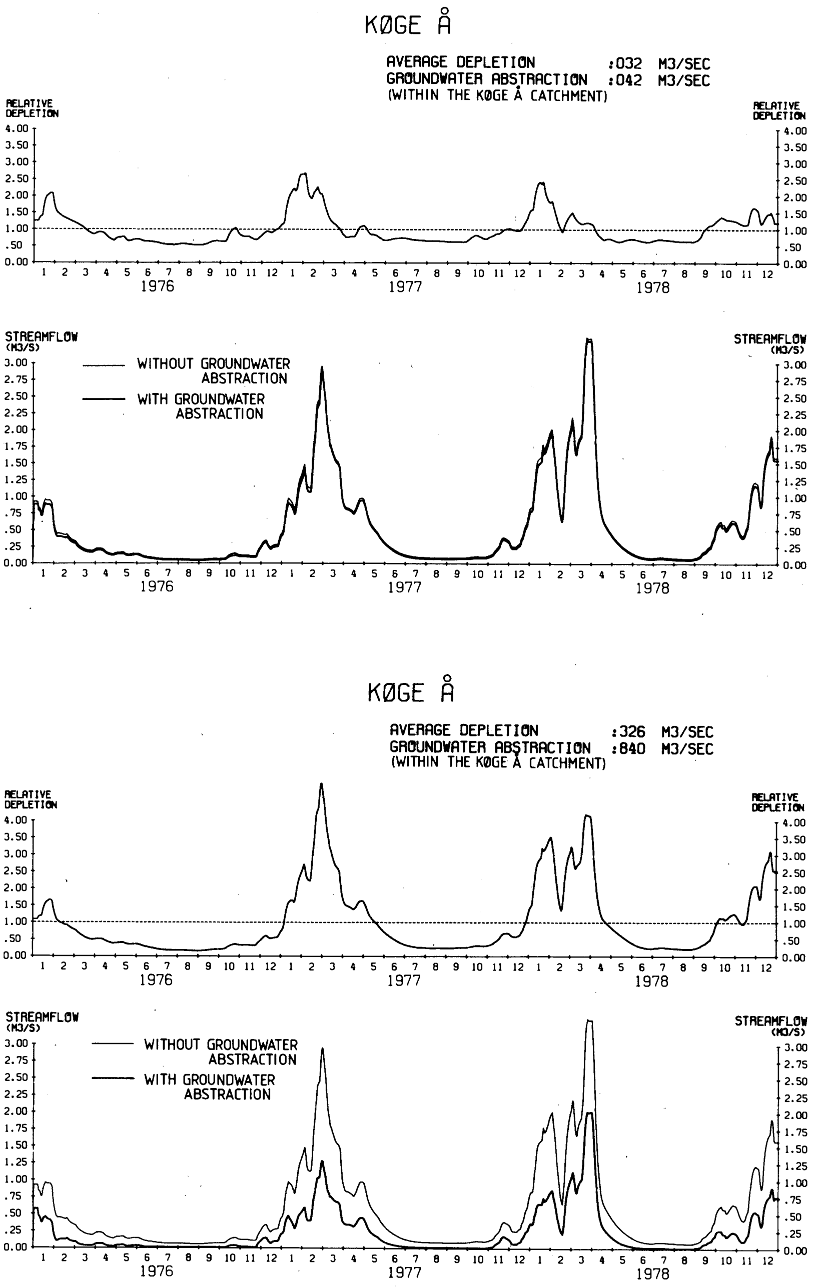

Fig. 5. Streamflow depletions in Køge Å caused by an additional groundwater abstraction of 10 mm/year (upper figure) and 200 mm/year (lower figure) within Køge Å catchment. All the streamflows are 15 days' moving average values.

In Fig. 4 the simulated streamflow with and without the groundwater abstraction is shown. It is also seen from the figure that the relative streamflow depletion varies between 0.4 and 4.0 for Tryggevælde Å, while it for Vedskølle Å varies between 0.1 and 7.4.

From a water quality point of view, the critical periods are the low-flow periods. Consequently, the most interesting depletion rates to be considered are the ones found at the time of the minimum flows. The relative depletions have been found to be almost constant from year to year for the same catchments, but vary considerably from catchment to catchment:

Vigersdal Å : 0.55-0.70
Køge Å : 0.55
Vedskølle Å : 0.05-0.10
Tryggevælde Å : 0.40-0.45
Suså/central : 0.55
Glumsø : 0.25-0.40

at an abstraction
of 25 mm/year

Re b): Varying Sizes of Groundwater abstraction

The streamflow depletion in Køge Å caused by an additional groundwater abstraction of 10 mm/year and of 200/yar within Køge Å catchment is shown in Fig. 5. Firstly, it is noticed that the larger the groundwater abstraction the larger the fraction of streamflow depletion from neighbouring catchments. At an abstraction rate of 10 mm/year, 10 l/s corresponding to 24% of the abstraction is, via subterrainean flow, depleted from streams in the neighbouring catchments, while at an abstraction rate of 200 mm/year it is 514 l/s corresponding to 61%. Secondly, it is noticed that the relative streamflow depletion curve changes considerably, so that a larger groundwater abstraction gives a more uneven seasonal distribution of the streamflow depletion. The reason for that can easily be seen, as also discussed above. When the streamflow from the entire catchment (or from a sub-catchment) has once reached zero in a low-flow period, an increase in the groundwater abstraction cannot further reduce the streamflow. Hence, the relative depletion decreases because the denominator (= the average depletion) increases, while the numerator (= the absolute depletion) remains constant.

Re c): Location of Sites for Pumping Wells

Today the commonly preferred sites for pumping wells in Danish groundwater schemes developing regional artesian aquifers are in the valleys close to the water courses. The main reason for this situation is the smaller drilling and pumping costs compared with alternative site selections for the wells.

In the following it has, by means of model simulations, been evaluated, if it is possible to minimize the streamflow depletion in the critical low-flow periods, by placing the pumping wells far away from the water courses.

In principle, the hydrological influence of the location of pumping well sites will be as follows. When the abstraction is placed far from the stream, the resulting drawdown in the hydraulic head is largest in recharge areas, implicating that the groundwater abstraction is compensated for by a large increase in recharge and a small decrease in groundwater discharge into the streams, via phreatic aquifers. When the abstraction is placed close to streams it results, on the contrary, in a smaller increase in recharge and a larger decrease in groundwater discharge into the streams.

To check the influence of the location of pumping well sites in quantitative terms, model simulations of groundwater abstractions were carried out for a high-transmissivity area ($T = 8 \times 10^{-2}$ m^2/s) as well as a low-transmissivity area ($T = 0.2 \times 10^{-2}$ m^2/s) within the Suså-catchment.

The simulation results showed that the well site location did hardly generate any difference in the streamflow depletion curve in the high-transmissivity area. The reason is that the drawdowns due to the large transmissivites are transmitted very efficiently, so that the cone of drawdowns becomes very flat. Even in the low-transmissivity area the location of the well site has only an insignificant influence on the relative streamflow depletion curves.

Consequently, it was concluded that the location of the well sites only has any influence on the streamflow depletion curves in areas where the transmissivities are so small that major groundwater developments are in general not possible.

Conclusions

The distributed groundwater/surface water model, presented in part I of this paper, has been successfully tested on historical streamflow data from the Køge Å catchment, which is heavily influenced by a groundwater abstraction.

The physical mechanisms of streamflow depletion, due to groundwater abstractions in catchments, where a confined aquifer is overlaid by Quaternary drift deposits, have been discussed and illustrated by some simulation results.

The large scale effects of a groundwater abstraction on the recharge and streamflow are illustrated.

The relative streamflow depletion has been shown to vary considerably from one catchment to another and to depend heavily on the size of the groundwater abstraction. Consequently it is not possible to assign a general streamflow depletion curve, neither to the entire Suså-area nor to the individual sub-catchments.

For confined aquifers it was found that the location of pumping wells in practice has negligible influence on the streamflow depletion.

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References

Refsgaard, J.C., and Hansen, E. (1982) A distributed groundwater/surface water model of the Suså area. Part I: model description. *Nordic Hydrology, 13 (5).*

Refsgaard, J.C., and Stang, O. (1981) An integrated groundwater/surface water hydrological model. Danish Committee for Hydrology. Report No. 13, 122 pp.

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