International Seminar on Hydrology of Extremes 1-3 December, 1988
Roorkee (India)

PREDICTION OF THE EFFECTS OF GROUNDWATER ABSTRACTION ON LOW FLOWS IN A MORAINE CATCHMENT

J. C. Refsgaard G. H. Jørgensen

Danish Hydraulic Institute, Agern Allé 5, DK-2970
Horsholm, Denmark

SYNOPSIS

A distributed groundwater/surface water model is described. Being a physically-based description of the entire land phase of the hydrological cycle, the model is the result of an integration of an integrated finite difference groundwater model, an aquitard model, a model for unconfined phreatic aquifers and a root zone model. The main objective of the model has been to make possible predictions of the hydrological consequences of groundwater abstraction on the river discharges and on the hydraulic heads of the aquifers. Therefore, special attention is given to the interaction between the streams and the aquifers. The model has been thoroughly tested against field data of streamflow, actual evapotranspiration, soil moisture deficit, drain water discharges and hydraulic heads of the confined aquifer. The paper gives a model description and a presentation of a case study of model application from a catchment in Denmark.

1.0 INTRODUCTION

The development of more powerful microcomputers has enabled a shift towards using complex hydrological models as practical instruments in the water resources planning and policy making. The models are being developed as user-friendly interactive tools which can be applied not only by trained modellers or specialists but also by practitioners involved in the water resource decision making.

Today traditional groundwater models are widely implemented on personal microcomputers and applied routinely in studies of groundwater developments. Unfortunately, these models are not suitable in evaluating the hydrological consequences on streamflow and water levels in lakes of given abstractions. In this case, integrated surface water/groundwater hydrological models, which describe the coupling between surface water and groundwater processes, are requested.

A well-tested integrated hydrological model for moraine areas, characterized with a lower confined reservoir overlayered with low permeable glacial deposits, is the so-called SUSAA-model.

This model was developed and applied at the Technical University of Denmark 1977-1982 during a Danish IHP research project in the Susaa Catchment (Hansen and Dyhr-Nielsen, 1983).

The SUSAA-model has been modified to be generally applicable to moraine areas and efforts have been made to improve the user-friendliness of the model for application on personal IBM PC/AT compatible computers. The modified software package called INGA, includes interactive modules for data setup, execution of the model and a graphic presentation of input and output.

The present paper gives a description of the model and a case study showing the application of the model to predict the effects of a major groundwater abstraction.

2.0 MODEL DESCRIPTION

The SUSAA-model can be applied to moraine areas, which in principle have the hydrogeological characteristics shown in Fig. 1, namely a lower regional confined aquifer, an aquitard and upper phreatic aquifers which are in contact with the river system. The model can be divided into three main sub-models:

- A model for the root zone calculating the actual evaporation, the soil moisture content and finally the percolation from the root zone to the upper phreatic aquifers. For the root zone calculations, the catchment is divided into sub-areas denoted precipitation areas with separate precipitation input and soil parameters. Spatial variation in vegetation is accounted for by subdividing each of the precipitation areas further into a number of different vegetation areas in accordance with the actual vegetation distribution within each precipitation area.

- A model for the phreatic aquifers and the aquitard, describing the discharge to the stream and the flow through the low permeable aquitard to the confined aquifer. The non-stationary aquitard flows are calculated by numerical integration of analytical aquitard response functions.

- A model for the confined aquifer, which is a two-dimensional groundwater model based on an integrated finite difference technique; involving the discretization of the catchment into a polygonal network.

In addition to these three main components the model includes minor sub-models for:

- Snowmelt consisting of a degree-day-model.

- Lakes. The lakes follow the shape of the polygons and a water balance is calculated.

- Wet areas close to the river system, where potential evaporation can be maintained throughout the year.

The time steps in the calculations are one day for all components of the model.

The overall structure of the model is outlined in Fig. 2.

For further details on the model description references are made to Stang (1981), Refsgaard (1981), and Refsgaard and Stang (1981).

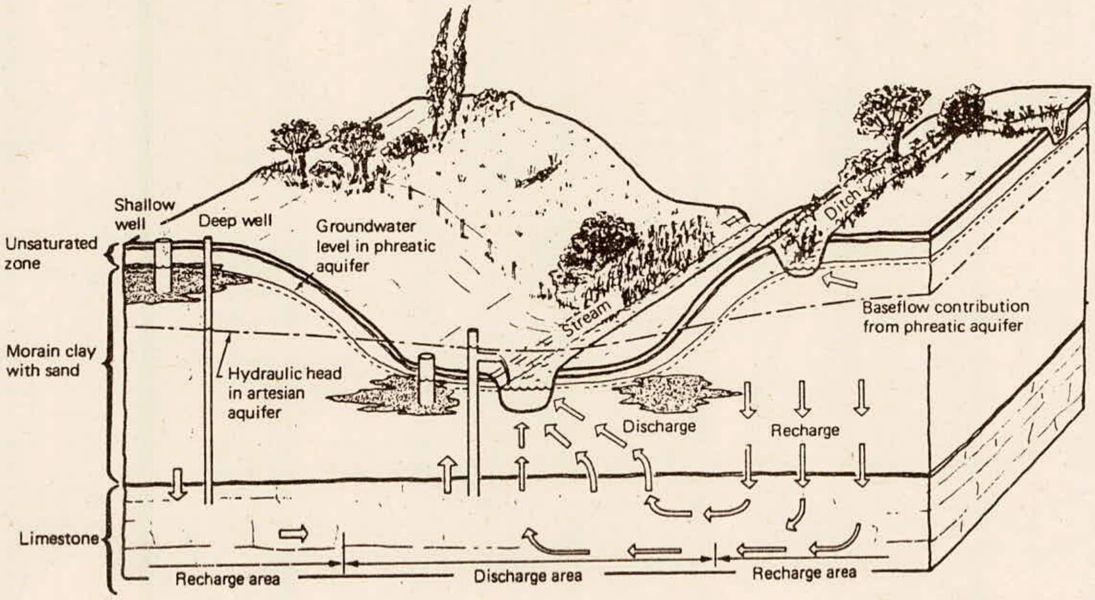
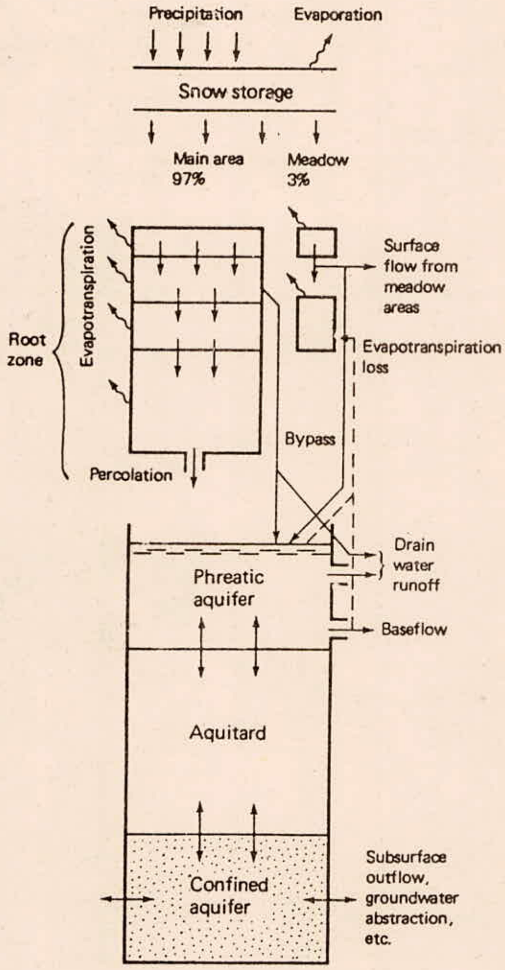


Fig. 1 The principle hydrogeological setup of a moraine area. Adapted from Hansen and Dyhr-Nielsen (1983).

3.0 MODEL SETUP AND GRAPHICS

The INGA-package is made user-friendly with respect to: data preparation, grid construction, execution, and presentation of data and results. All these phases are carried out interactively.

In each application the polygonal network for the groundwater model is initially established by digitizing all node values of the network. All calculations of geometrical values are carried out automatically. When required the network can be changed easily. Fig. 3 shows an example of how a polygon has been divided into 15 smaller polygons.



Model distribution		Model parameters	
Lumped 7 sub-areas		Degree day factor	
Main area	Meadow	Main area	Meadow
Lumped 7 x 5 sub-areas	Lumped 7 sub-areas	Evapotransporation parameters Leaf-area index Root-distribution factor Root depths Field capacity Wilting point Threshold values Bypass constants	Storage capacities Meadow area in each polygon Evapotranspiration loss coming from baseflow or from phreatic aquifer
112 x 4 sub-polygons		Storage coefficient time constants	
112 x 4 sub-polygons		Hydraulic conductivity specific storage	
112 polygons		Transmissivity storage coefficient	

Fig. 2 The vertical structure, spatial distribution, and parameters of the hydrological model. The spectric number of sub-areas refers to the case study presented below.

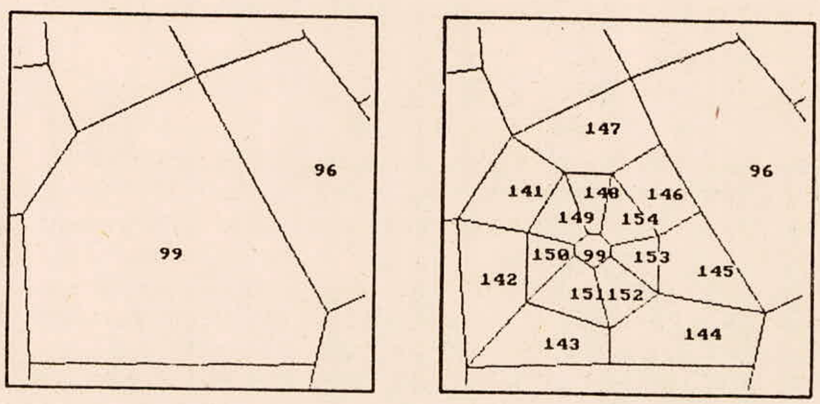


Fig. 3 Example of sub-division of a polygon to many smaller polygons.

All the difficulties and the time consuming part using a polygonal network compared with a rectangular network are hereby eliminated and the advantages of a polygonal network can then be utilized. A polygonal network is more flexible; it can be detailed in interest areas with e.g. groundwater abstraction, rivers, lakes, or highly variable hydrogeological parameters, while uninteresting areas mainly included for assuring correct boundary conditions can be represented by larger polygons. A polygonnet will therefore have fewer computational points than a traditional rectangular net, often 5-10 times less.

The model execution takes place interactively where simulation period and the type and amount of output are specified.

All results from the model simulation can be retrieved and presented in tables or displayed by means of the graphical display routine. This graphical display package is an interactive menu driven routine, which can be used for presentation of input or output data. It is possible to draw theme maps of the network in a selected scale and time series of measured and simulated values can be displayed. Examples are presented in Fig. 6.

4.0 CASE STUDY. KOEGE AA

The study area, including the catchments of Susaa and the neighbouring catchments Koege Aa, Vedskoelle Aa and Tryggevaelde Aa, covers about 1000 km^2 of the central and southern part of Zealand, at a distance of 50-70 km south-west of Copenhagen. The model area, the topographic divides, and the groundwater model polygonal mesh are shown in Fig. 4.

The water supply of municipalities and industries within the basin is generally based on low-intensity groundwater abstraction schemes. However, a centralized high-intensity groundwater abstraction for Copenhagen of approximately 15 million m^3/year is located around Regnemark within and just outside the north-eastern part of the catchment. The groundwater abstraction during the 1950-80 period is shown in Fig. 5.

A transmissivity map is given in Fig. 6 showing variations from less than 2 to more than 300 x 10^{-4} m^2/s throughout the model area. Fig. 7 shows the simulated piezometric head levels at day 360, 1977.

4.1 Model Calibration and Test

Examples of simulations of the hydraulic heads are shown in Fig. 7 together with data from observation wells. The calibration of the groundwater model was primiarly based on a steady state simulation of the 1974 heads, and on simulations of the seasonal fluctuations in the 1974-80 period. However, both the seasonal fluctuations and the levels for the period prior to 1974 are seen to be

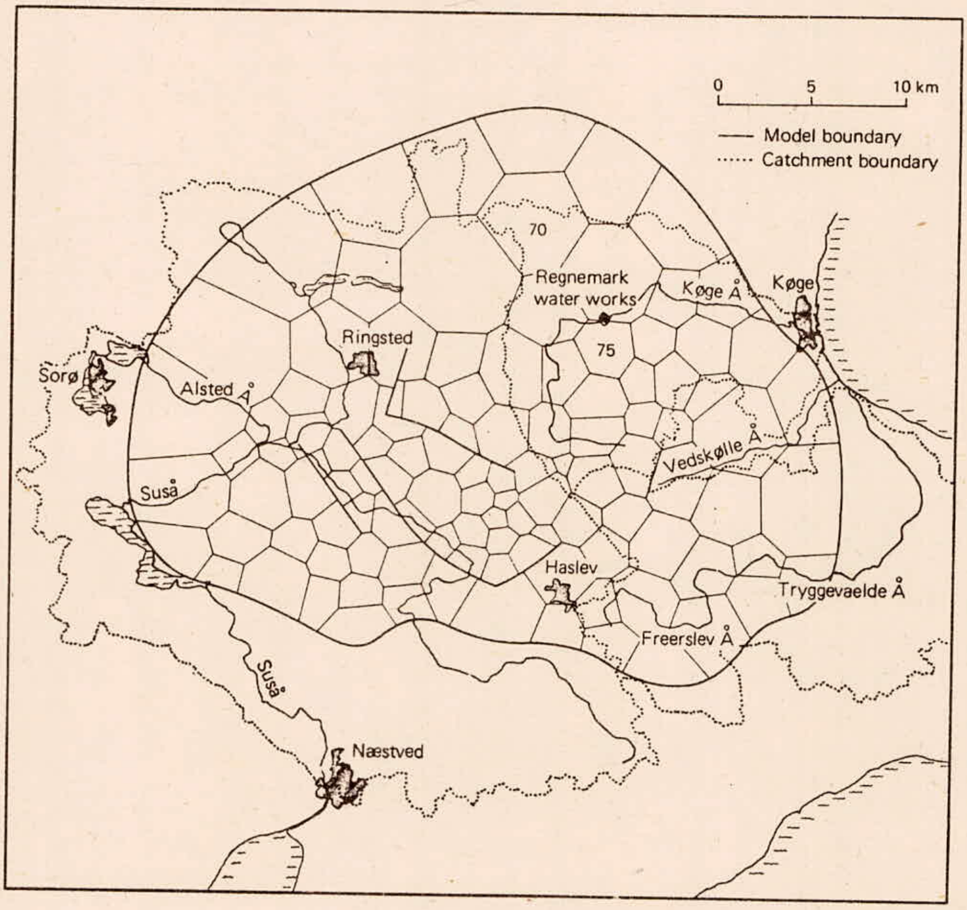


Fig. 4 Model area, catchment boundaries and groundwater polygonal grid.

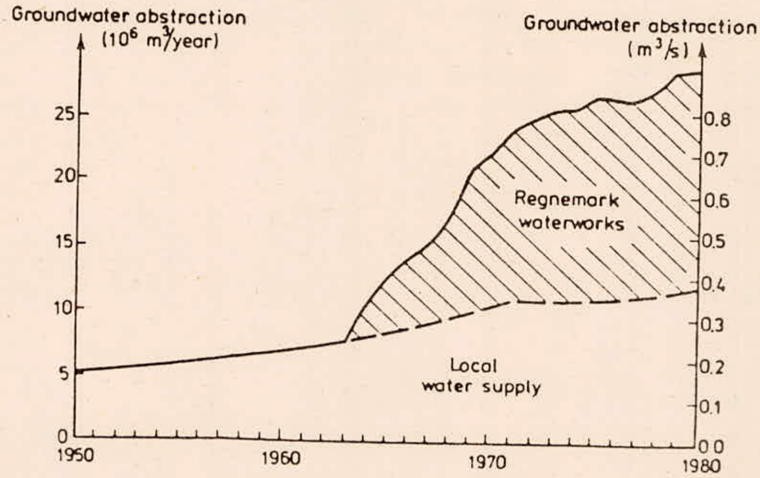


Fig. 5 The groundwater abstraction during the 1950-80 period within the 940 km^2 area covered by the groundwater model.

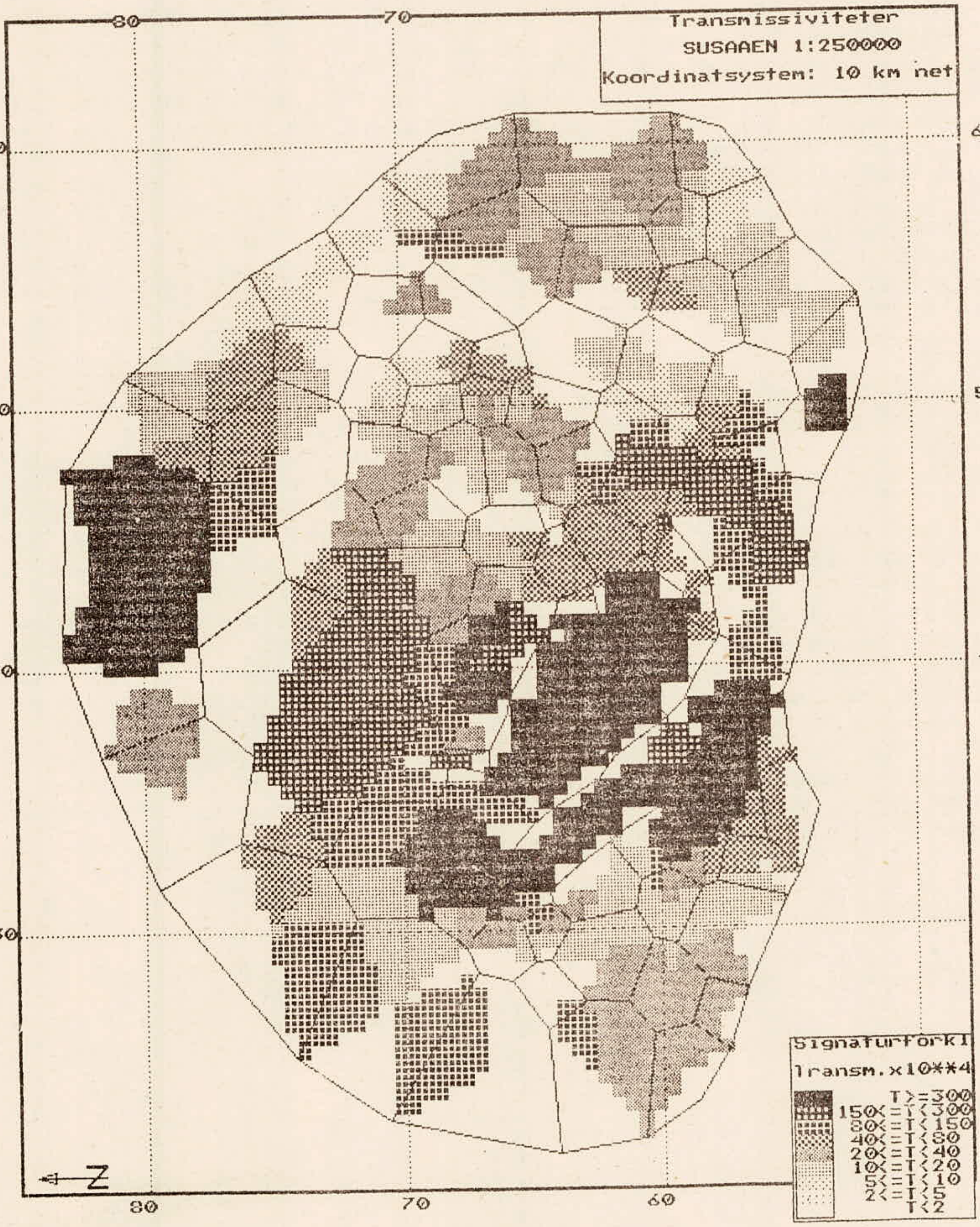


Fig. 6 Transmissivity map for the confined aquifer. Transmissivity scale 2-300 10^{-4} m^2/s.

simulated reasonably well. The differences between the polygons in the amplitudes of the seasonal fluctions are primarily caused by variations in aquitard thickness (dampening effect) and in groundwater abstraction (oscillatory effect). It is noticed that the effects of a comprehensive groundwater abstraction, started in 1964 in the area close to the polygons 70 and 75, are simulated rather well, both with respect to the drawdowns and to the increase in the amplitude of the seasonal fluctuations. The difference between observed and simulated head in polygon 70 during 1958-65 is mainly due to a too course space discretization in this area. Thus, the natural variation in head within polygon 70 is more than 5 metres. These simulations thus serve as very encouraging tests of the model dynamics and of the model's ability to simulate the effects of variations in both climatological variables and groundwater abstraction.

As an example of the models ability to simulate the root zone processes, the simulated soil moisture deficits in the root zone of the beet vegetation are shown in Fig. 8 together with the measured values from an experimental station in the middle of the area. For the entire root zone a very good agreement is seen.

As an example, streamflow simulations from the 133 km^2 Koege Aa catchment are shown in Fig. 9 for the two periods 1961-63 and 1974-76. It is noticed that the river, as a consequence of the groundwater abstraction started in 1964, dries up every summer in the second period (1974-76). The parameter values, used in the root zone model for the Koege Aa catchment, have not been found by calibration in the Koege Aa, but have been taken identical to the parameter values from the neighbouring catchment, Lilleaa. The only parts of the model which have been calibrated beforehand are the groundwater model of the confined aquifer and aquitard model. Thus the simulation shown in Fig. 9 is a half-way test of the model's ability to simulate streamflow in ungauged catchments.

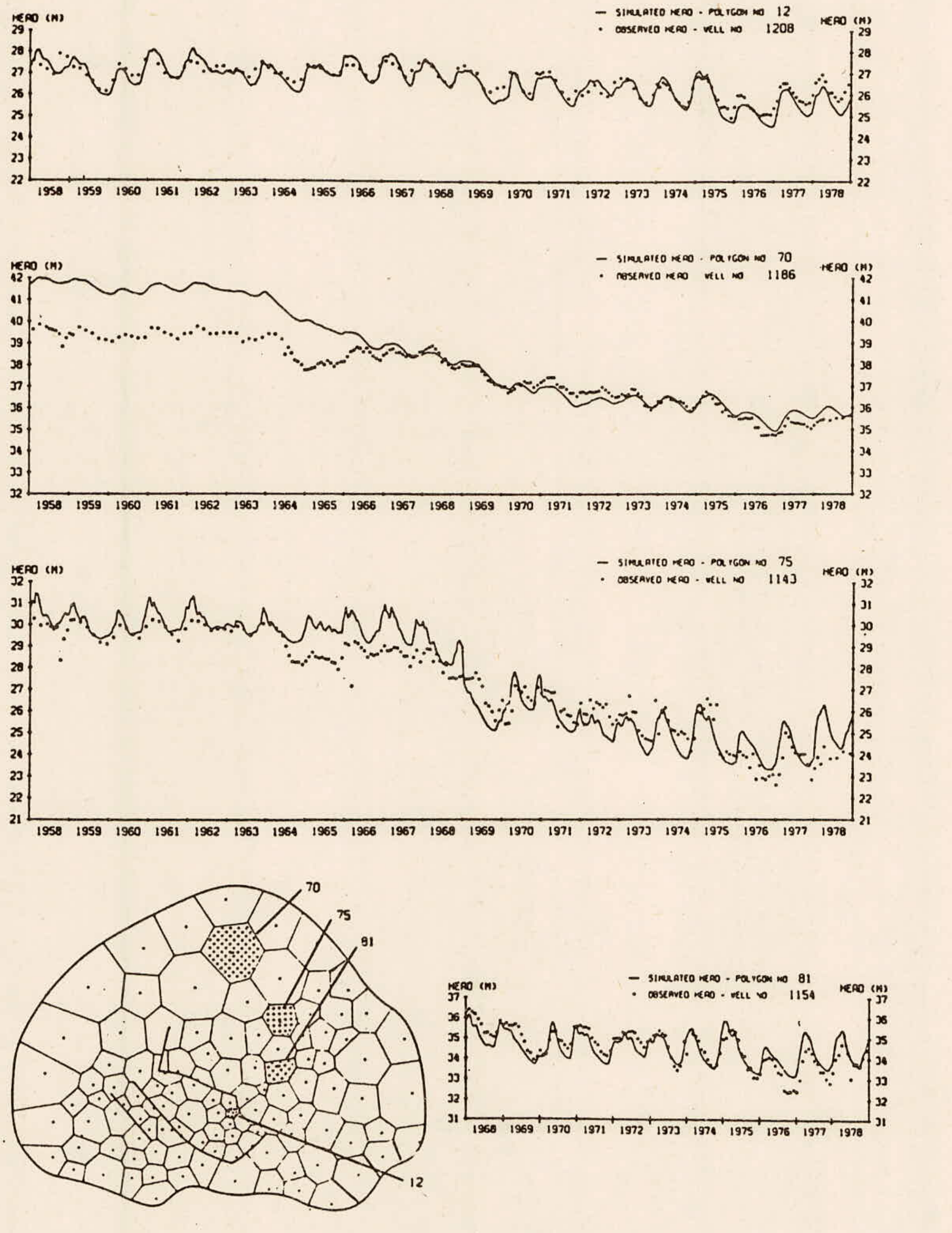


Fig. 7 Comparison of the simulated and observed piezometric heads of the confined aquifer.

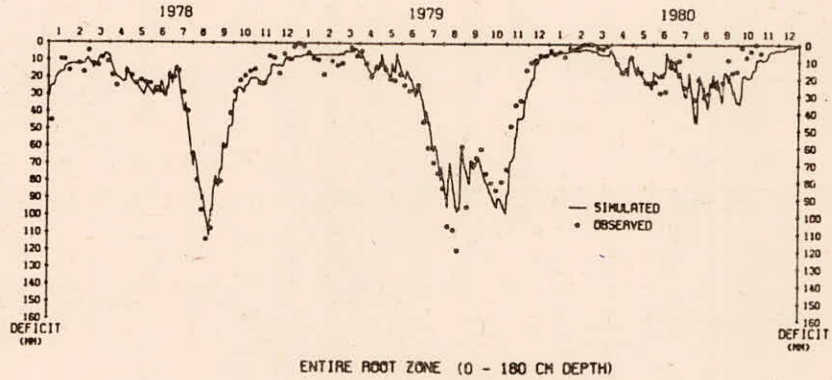


Fig. 8 Measured and simulated soil moisture deficits in the root zone of the beet vegetation.

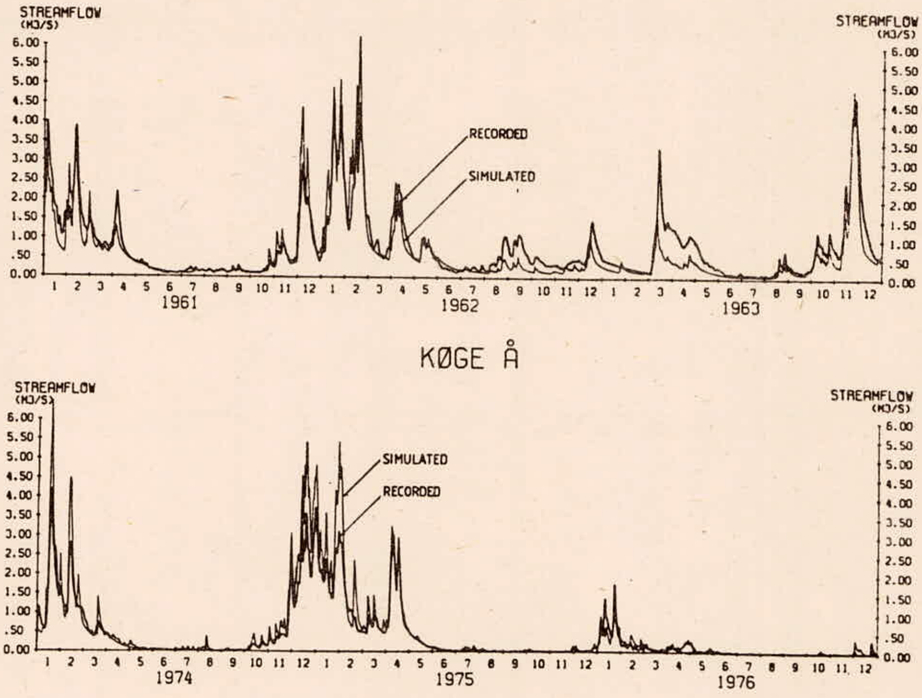


Fig. 9 Comparison of simulated and recorded streamflow for the 133 km^2 Koege Aa catchment. The streamflow in the period 1974-76 is influenced by a comprehensive groundwater abstraction within the catchment, started in 1964.

4.2 Effects 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 increeased, due to a decrease of the groundwater abstraction, and due to a larger recharge to the phreatic aquifers than in the preceeding very dry year of 1976.

The recharge and discharge rates vary very few per cent 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.

Table 1 The Water balance of the confined aquifer.

	1953 (m^3/s)	1977 (m^3/s)	Change 53-57 (m^3/s)
Groundwater abstraction	0.176	0.830	+0.654
Leaking wells (Susaa)	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	

5.0 CONCLUSIONS

The INGA model is a further development of the SUSAA integrated surface water/groundwater model generally applicable to areas with regional confined aquifers. The model has been generalized and made more user friendly and easy to setup and apply on PC/AT computers.

Results from a model application to the Koege Aa catchment in Denmark have been shown and discussed.

An integrated surface water/groundwater model is especially applicable for the following purposes, of which some have been demonstrated in the paper.

- Prediction of low flows.
- Study of groundwater abstraction and its influence on the piezometric heads and recharge.
- Assessment of the hydrological consequences of a groundwater abstraction on water levels and discharges in lakes and streams.
- Conjunctive use of surface water and groundwater.

6.0 REFERENCES

Hansen, E. and Dyhr-Nielsen, M. (1983): The Susaa project: Modelling for water resources arrangement. Nature and Resources, Vol. 19, No. 3, pp. 10-18.

Refsgaard, J.C. (1981): The surface water component of an integrated hydrological model. Danish Committee for Hydrology. Report SUSAA H 12, 108 pp.

Refsgaard, J.C., and Hansen, E. (1982): A distributed groundwater/surface water model for the Susaa-catchment. Part I: Model description and Part II: Simulations of streamflow depletion due to groundwater abstraction. Nordic Hydrology, Vol. 13, No. 5, pp. 299-322.

Refsgaard, J.C., and Stang, O. (1981): An integrated groundwater/surface water hydrological model. Danish Committee for Hydrology. Report SUSAA H 13, 122 pp.

Stang, O. (1981): A regional groundwater model for the Susaa area. Danish Committee for Hydrology. Report SUSAA H 9, 112 pp.

1988-09-21
1006-1/wrdp11
JCR/skn