*Nordic Hydrology*, 13, 1982, 299-310

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

## Part I – Model Description

**Jens Chr. Refsgaard and Eggert Hansen**
Technical University of Denmark, Copenhagen

A distributed hydrological model has been developed for the Suså catchment, covering about 1,000 km$^2$ of Zealand, Denmark. 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 was tested against field data of streamflow, actual evapotranspiration, soil moisture deficit, drain water discharges and hydraulic heads of the confined aquifer. A model description and some results from the calibration and tests are given.

## Introduction

Rainfall-runoff models and groundwater models are two different kinds of models which during the last decade have been applied extensively in water resources management. The rainfall-runoff models introduced by surface water hydrologists, usually take account of the groundwater reservoir by means of a very simple black box model for routing recharge into streamflow. The groundwater models, introduced by geohydrologists, usually consider the recharge and the discharge into streams as boundary conditions, which are found by means of hydraulic head calibrations.

If a groundwater abstraction, the consequences of which are to be simulated by a groundwater model, is relatively small compared with the recharge and the discharges to streams, a traditional groundwater model is usually adequate. However, if a groundwater abstraction is relatively large, special attention should be given to the modelling of the interaction between the surface and the subsurface parts of the hydrological cycle. In this case it is of vital importance to estimate the recharge and discharge rates in time and space as correctly as possible. Also, if the interaction between the groundwater reservoirs and the streams is an important issue, a coupling of a surface water model and a groundwater model is crucial.

In recent years several authors have concluded that a coupling between surface water models and groundwater models in many cases is necessary to make optimal planning of the water resources. However, so far only a few attempts have been made to build integrated surface water/groundwater models. Weeks et al. (1974), Wardlaw (1978), Jønch-Clausen (1979), Storm and Refsgaard (1980), and Refsgaard and Stang (1981) have presented various surface water/groundwater models, developed for various purposes and for various hydrogeological conditions.

The main objectives of the present study have been

- To develop a spatially distributed groundwater/surface water model for the Suså catchment. The model should be able to simulate seasonal as well as year-to-year variations in the hydrological regime of the catchment as a consequence of varying meteorological and climatological conditions, as well as of the influence of man.
- To improve our present understanding of the physical mechanisms of the stream-aquifer interaction in a geohydrologic system consisting of confined aquifer-aquitard-phreatic aquifers.
- To develop the model on a physically sound basis with special attention to the interaction between the streams and the aquifers.
- To develop the model as a tool applicable for prediction of the hydrological consequences on streamflows and hydraulic heads of groundwater abstraction.

In part I of this paper the model description and some results from the calibration and tests are given, while the physical mechanisms of streamflow depletion due to groundwater abstraction are given special attention in part II (Refsgaard and Hansen 1982). A comprehensive description of the model and simulation results are given in Stang (1981), Refsgaard (1981), and in Refsgaard and Stang (1981).

## The Suså-Catchment – A Brief Description

The Suså catchment is situated in the central and southern part of Zealand, 50-70 km SW of Copenhagen. The model area, the topographic divides, and the groundwater model polygonal mesh are shown in Fig. 1. A simplified geological north-

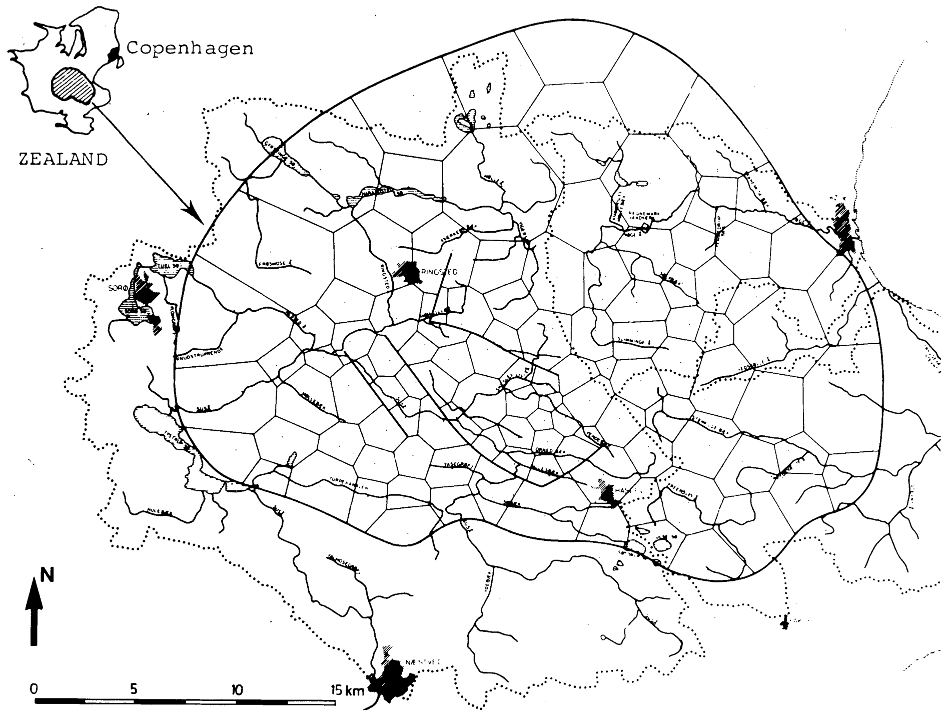


Fig. 1. Model area, topographic divides, and groundwater polygonal mesh.

south cross section is shown in Fig. 2.

The landscape is a moraine landscape formed by glaciers during the last glacial period. The pre-Quaternary aquifer consists of Paleocene deposits and Danian limestone. It is overlayered by glacial deposits, predominantly consisting of moraine clay, yet with some few areas with sandy soil. The thickness of the glacial deposits ranges from less than 10 metres in a few places in the central part of the catchment, to more than 100 metres in the north-western parts.

The phreatic water table in the moraine deposits is observed to be highly dependent on the topography, and is generally situated a couple of metres below the ground surface. Similar conditions was previously observed by Gustafsson (1968) for several locations in Sweden.

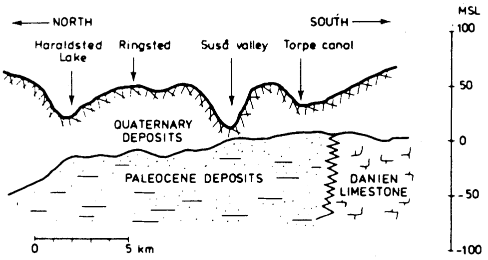
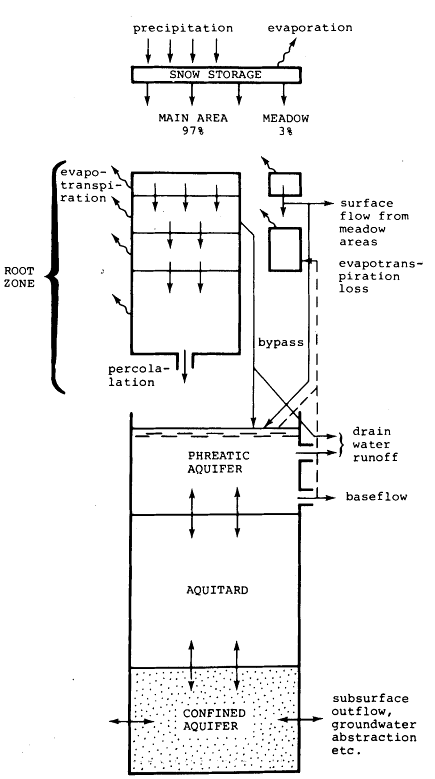


Fig. 2.
A simplified, geological north-south cross section through Ringsted.



| MODEL DISTRIBUTION | | MODEL PARAMETERS | |
|---|---|---|---|
| lumped<br>7 sub-areas | | degree day factor | |
| MAIN AREA<br>lumped<br>7 x 5 sub-areas | MEADOW<br>lumped<br>7 sub-areas | MAIN AREA<br>evapotranspiration parameters<br>leaf-area-index<br>root distribution factor<br>root depths<br>field capacity<br>wilting point<br>threshold values<br>bypass constants | MEADOW<br>storage capacities<br>meadow area in each polygon<br>evapotranspiration loss coming from baseflow or from phreatic aquifer |
| 112 x 4<br>sub-polygons | | storage coefficient<br>time constants | |
| 112 x 4<br>sub-polygons | | hydraulic conductivity<br>specific storage | |
| 112 polygons | | transmissivity<br>storage coefficient | |

Fig. 3. The structure of the distributed surface water/groundwater model.

## Model Description

The overall structure of the model is outlined in Fig. 3. As may be observed, the model consists of four separate components for the confined regional aquifer, the aquitard, the phreatic aquifers and the root zone, respectively. The time steps in the calculations are one day in all parts of the model.

### Confined Aquifer Component

The nearly horizontal groundwater flow in the pre-Quaternary confined regional aquifer is accounted for by a traditional, spatially distributed, two-dimensional model of the integrated finite difference type (Thomas 1973).

The spatial discretisation is achieved by means of a polygonal mesh containing 112 polygons, see Fig. 1.

The calibrations and the test of the confined aquifer model are described in Stang (1981), where also the parameter values are discussed. The transmissivities vary from $8 \times 10^{-2} m^2/s$ in the central part of the area to less than $10^{-3} m^2/s$ in other parts, while the storage coefficients vary within the range $1 \times 10^{-4} - 12 \times 10^{-4}$.

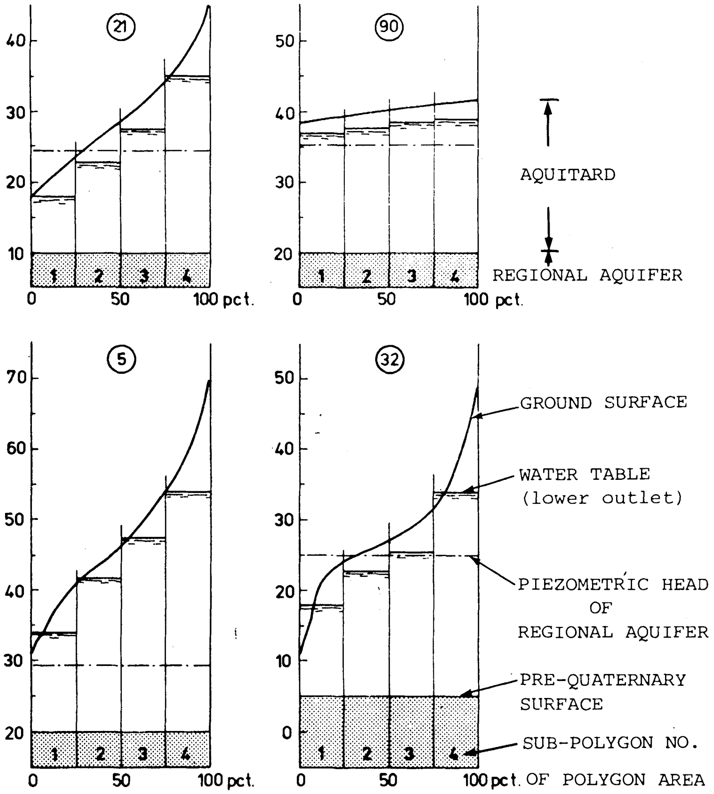


Fig. 4. Hypsographic curves for 4 selected polygons.

### Phreatic Aquifer Component

As previously mentioned, it is a characteristic feature of the phreatic aquifer that the water table elevation, although not constant in time, is highly dependent on the topography. The local vertical exchange of water between the phreatic and the confined regional aquifer depends on the height difference between the water table and the piezometric head of the regional aquifer. From the hypographic curves shown in Fig. 4, it is evident that the exchange rate may vary considerably within a polygon. Recharge areas, having downward flow from the phreatic to the confined aquifer, as well as discharge areas, characterized by upward flows, are often experienced within the same polygon. As the discharge to the phreatic aquifers gives rise to the main part of the baseflow contributions to the streams in dry summer periods, it is of the utmost importance for a correct simulation, especially of low streamflows, that the water exchange mechanisms are appropriately modelled.

Consequently, on the basis of surface topography, the phreatic aquifers in each

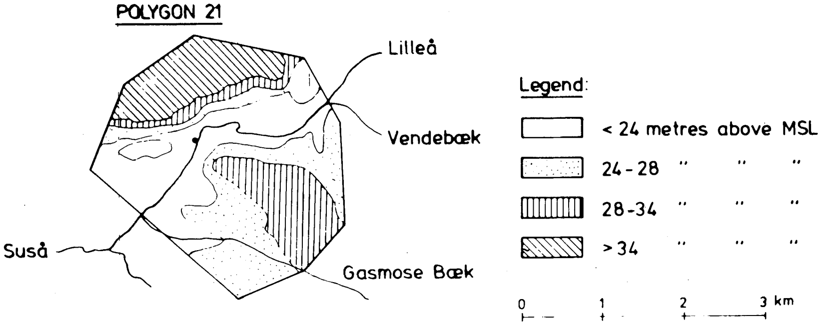


Fig. 5. Division of polygon 21 into 4 sub-polygons.

polygon have been divided into four equally large sub-areas, assuming homogeneous recharge and discharge conditions within each sub-area, see Fig. 4. For part of the Lilleå catchment it is shown in Fig. 5 how polygon 21 is subdivided in »sub-polygons« (that are not at all polygonal in shape). No horizontal water exchange is assumed in between the individual phreatic aquifers, described by this process.

Horizontal water movements in the phreatic aquifers are modelled as a direct routing of run-off from each reservoir to the streams. Two outlets at different elevations yield the drain water runoff and baseflow component, respectively. The routing mechanism is that of a linear reservoir. The time constant used for the upper outlets is about 10 days, while it is about 30 days for the baseflow component.

In each of the 448 sub-polygons the levels of the two outlets (lower outlet for baseflow and upper outlet for drain water runoff) have been determined from the hypsographic curves, the lower outlet located 2-3 m below average ground surface in the subpolygon, and the upper outlet located about 1 m below ground surface. The water tables for each sub-polygon in Fig. 4 are shown at the level of the lower outlet. Actually, the water tables are time varying, being above both outlets in the wet periods of the year, with large percolation through the root zone. At the end of the dry season, the water tables will be below the lower outlets in most of the sub-polygons with the result that there is no contribution to the streamflow from these sub-polygons. In such periods the water level will be above the lower outlet only in the subpolygon where the water flow in the aquitard is upward. The specific yield of the phreatic aquifer is assumed to be 0.010-0.015.

## Aquitard Component

The coupling between the confined aquifer and the phreatic aquifers is simulated by a one-dimensional model of the Quaternary boulder clay aquitard, where only vertical flow is assumed to take place. The flows between the phreatic aquifers and the aquitard, and between the aquitard and the confined aquifer are calculated by superposition of three contributions, one accounting for steady recession and two for the non-stationary flows, caused by changes in head, either in the phreatic aquifers (e.g. by replenishment from the root zone) or in the confined aquifer (e.g. by changes in the groundwater abstraction). In all three cases the storage capability of the aquitard is taken into account. The non-stationary flows are calculated by numerical integration of analytical aquitard response functions, which have been obtained by a procedure previously described by Frind (1979).

The parameters in the aquitard model, the specific storage and the hydraulic conductivity in principle vary within the 448 subpolygons. However, the specific storage has been taken as $10^{-4}m^{-1}$ in all the sub-polygons. Similarly, the hydraulic conductivity equals $5 \times 10^{-9}$ m/s in more than 90% of the area, the larger values only occurring in areas with sandy aquitards.

### Root Zone Component

Spatial variations in precipitation and in soil physical properties are accounted for by dividing the 1,100 km$^2$ area into seven sub-areas, denoted precipitation areas, with separate precipitation input and soil parameters. Spatial variations in vegetation are accounted for by sub-dividing each of the seven precipitation areas further into five vegetation areas (and one meadow area) in accordance with the actual vegetation distribution within each precipitation area. Each of the 35 sub-areas is then modelled with the same lumped type model, but with different parameters. The root zone is divided into four layers in which the moisture content is calculated on a daily basis by bookkeeping of gains (net vertical flows) minus losses (actual evapotranspiration, calculated by a slightly modified version of the model presented by Kristensen and Jensen 1975).

In order to account for nonhomogeneities in the soil, minor but quickly responding bypass contributions to streamflow and percolation have been incorporated, see Fig. 3. In addition to the five vegetation areas, a simple meadow routine has been introduced, covering only 3% of the total catchment, for which potential evapotranspiration is assumed to be maintained all the time, due to ample water supply.

The outflows from the root zone component to the streams (bypass) and to the phreatic aquifers (bypass and percolation) are lumped within each precipitation area; weighted averages are made according to the areal distribution of the five vegetation types and the meadow within the precipitation area.

The parameters of the root zone components consist of physical entities (field capacity, wilting point, leaf area index, root depth) obtained from field measurements, as well as 12 semi-empirical constants, determined by calibration. However, only three out of the twelve semi-empirical constants vary from one subcatchment to another. Thus most of the variation in the hydrological regime from catchment to catchment is explained by variations in the physical parameters, the topography, the vegetation distribution and the meteorological input, but not in variations in the semi-empirical parameters.

## Simulation Results

In the calibration and test of the model historical time series of both hydraulic heads of confined aquifer, streamflows and soil moisture contents in the root zone have been considered.

### Hydraulic Heads of Confined Aquifer

Examples of simulations of the hydraulic heads are shown in Fig. 6 together with data from observation wells. The calibration of the groundwater model was primarily 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 simulated reasonably well. The differences between the polygons in the amplitudes of the seasonal fluctuations 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 course space discretisation 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.

### Soil Moisture Content in Root Zone

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. 7 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.

### Streamflow

As an example, streamflow simulations from the 133 km$^2$ Køge Å catchment are shown in Fig. 8 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 Køge Å catchment, have not been found by calibration in the Køge Å, but have been taken identical to the parameter values from the neighbouring catchment, Lilleå. 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. 8 is a half-way test of the model's ability to simulate streamflow from ungauged catchments.

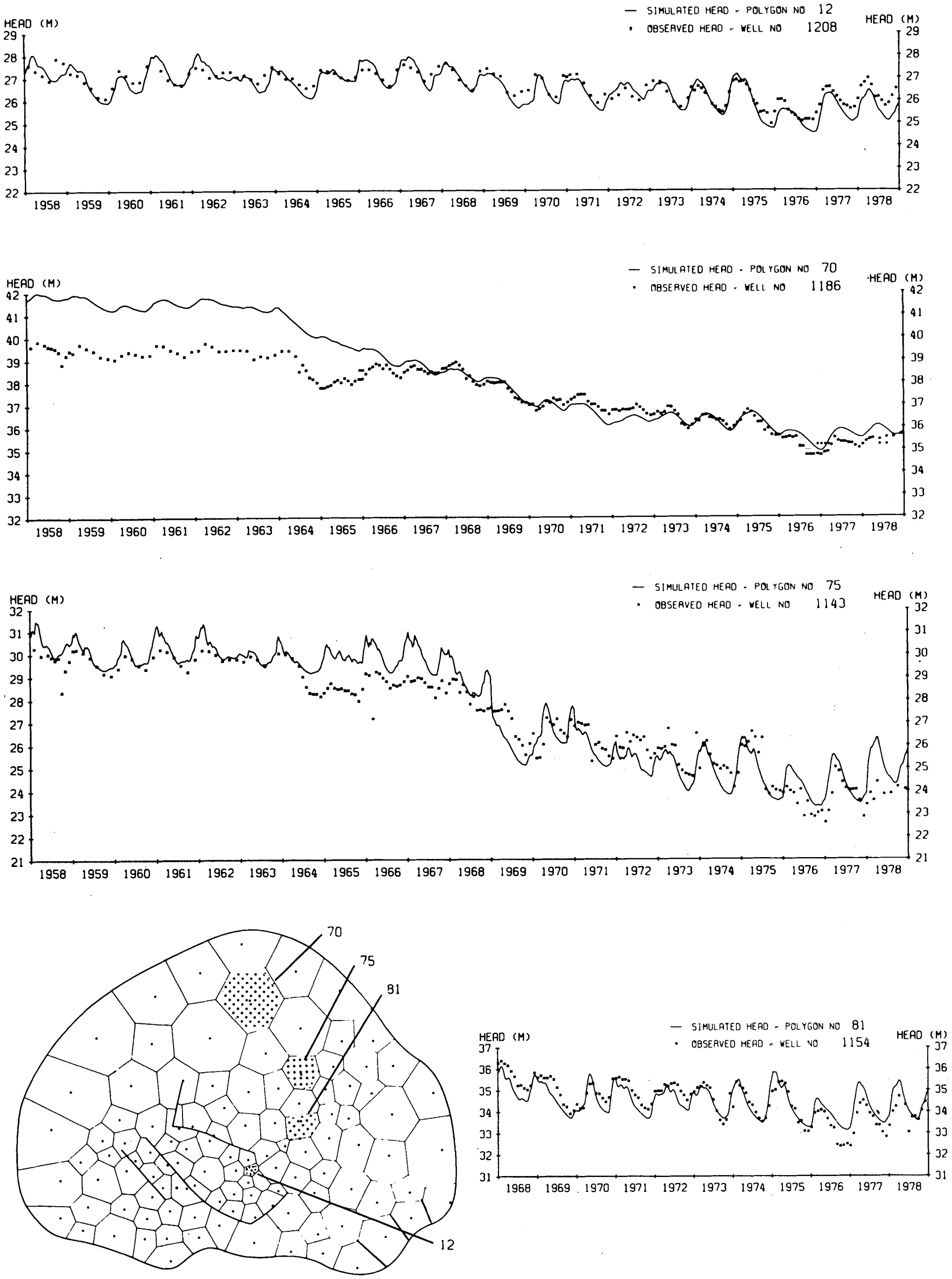


Fig. 6. Comparison of simulated and observed hydraulic heads of the confined aquifer.

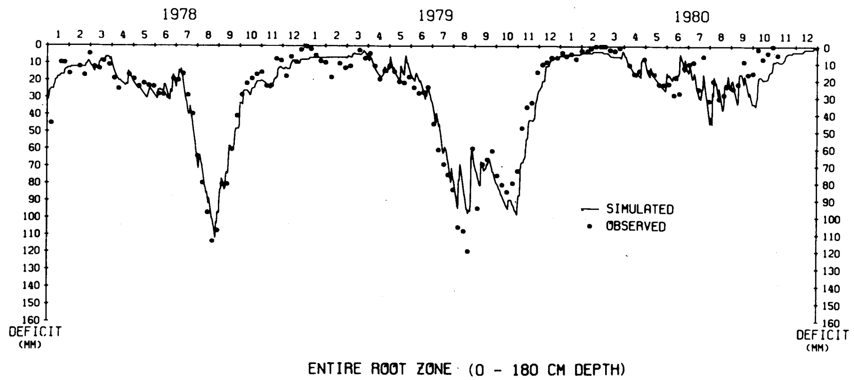


Fig. 7. Measured and simulated soil moisture deficits in the root zone of the beet vegetation.

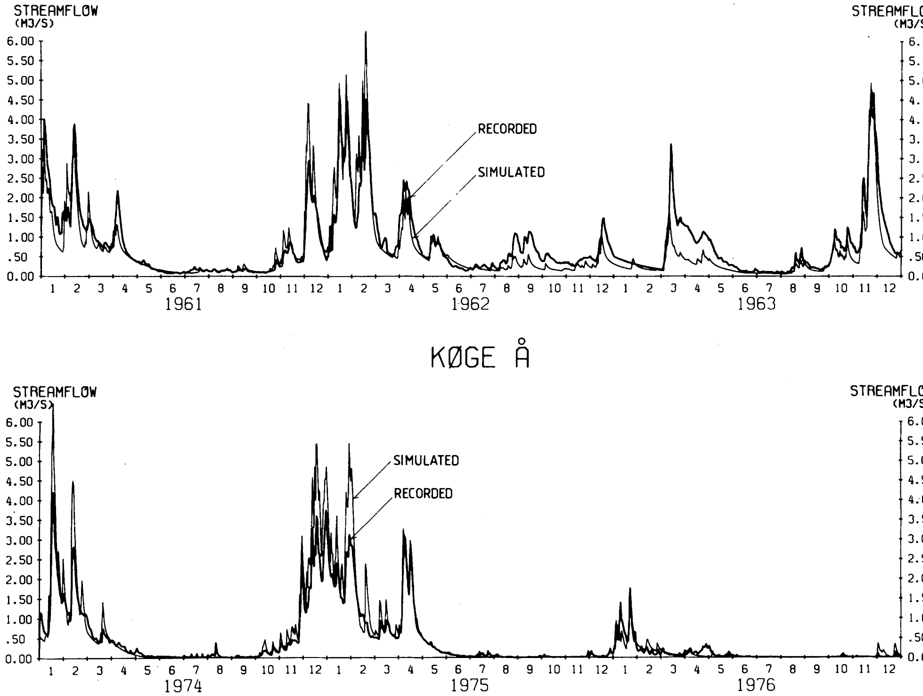


Fig. 8. Comparison of simulated and recorded streamflow for the 133 km$^2$ Køge Å catchment. The streamflow in the period 1974-76 is influenced by a comprehensive groundwater abstraction within the catchment, started in 1964.

## Conclusions

A spatially distributed groundwater/surface water model has been developed for the Suså-catchment. The model gives a physically based description of the main processes in the entire land phase of the hydrological cycle. The model simulates seasonal as well as year-to-year variations in the hydrological regime of the catchment as a consequence of changing hydro-meteorological and climatological conditions as well as of the influence of man. Almost all the model parameters are physical parameters such as transmissivities, storage coefficients, topographical data, field capacity, leaf area index etc. The model has a general applicability in areas with similar hydrogeological conditions, i.e. a lower confined aquifer with relatively large transmissivities overlayered by low permeable saturated deposits (e.g. moraine clay) and the phreatic surface rather close to terrain.

Calibration and test simulations have been presented for the Suså-catchment, with respect to hydraulic heads of the confined aquifer, streamflow and soil moisture. Seasonal and year-to-year variations in the hydrological regime have been considered.

## Acknowledgements

This study was carried out as part of a Danish IHP research project in the Suså-catchment. The project was financed by the Danish Agency of Environmental Protection, the Danish Agricultural and Veterinary Research Council, the Danish Natural Scientific Research Council, the Danish Council for Scientific and Industrial Research, and the Danish Council of Technology.

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Received: 22 October, 1982

**Address:**
Institute of Hydrodynamics and
Hydraulic Engineering, ISVA,
Bldg. 115,
Technical University of Denmark,
DK-2800 Lyngby,
Denmark.

J. Chr. Refsgaard now also at
Danish Hydraulic Institute,
Agern Allé 5,
DK-2970 Hørsholm,
Denmark