Nordic Hydrology, 13, 1982, 323-338

Water Resources Planning in the Suså-Basin by Means of a Simulation Model

Jesper Knudsen
Technical University of Denmark, Copenhagen, and
Danish Hydraulic Institute, Hørsholm, Denmark

Dan Rosbjerg
Technical University of Denmark, Copenhagen

As part of the »Suså-project« a combined hydrological/water quality simulation model has been developed for water resource planning purposes. The model provides a detailed analysis of the consequences of meeting the demands of conflicting interests (water supply, waste water disposal, irrigation, recreation). The model is presented along with simulation results for a number of different dispositions of the water resource, in order to illustrate the applicability.

Introduction

In Denmark, water resources planning is carried out on a regional level and involves the consideration of sector interests such as water supply, recipient quality, waste water disposal, irrigation and conservation of water areas. Recognizing the interdependency of individual sector plans, recent legislation has stressed the needs for multiobjective, coordinated planning. Specifically, the new water resources development act claims an overall, coordinated plan on the regional level, paying due attention to individual sector interests.

Achieving this objective requires ideally a tool that makes it possible to evaluate the effects of any water resource scheme and determine the associated tradeoffs between competing demands. The current planning practice of regional water authorities, however, relies in general on rough methods to assess the impacts of specific schemes.

The aim of the management part of the Suså project was to evaluate the possibilities of providing a more rational and comprehensive basis for coordinated water resources planning. In particular, the scope of this study has been to develop a combined hydrological/water quality model for the Suså-basin, which could simulate the integrated effects of

- combined development of ground- and surface water for water supply purposes
- groundwater abstraction for irrigation purposes
- low flow argumentation for the maintenance of adequate stream flows
- treatment and discharge of sewage.

Operation of the model enables quantitative conclusions to be drawn about the hydrological and water quality consequences of various alternatives for water resources utilization in the Suså-area, which may be used to determine guidelines for the future development of the water resources.

The study presented in this paper was carried out by the Danish Land Development Service, the Water Quality Institute and the Institute of Hydrodynamics and Hydraulic Engineering.

The Present Water Resources Utilization in the Suså-Basin

The areal extent of the simulation model is shown in Fig. 1 and covers the main part of the Suså-basin plus two adjacent basins drained by the streams Køge Å and Tryggevælde Å respectively, in total approximately 1,000 km^2. A number of different and partly competing interests are concerned in the water resources of this area.

The water supply of municipalities and industries within the basin is generally based on low-intensive groundwater abstraction schemes. However, a centralized high-intensive groundwater abstraction is located in the northern part of the area in favour of the city of Copenhagen. In addition to this the city of Copenhagen uses the two lakes Haraldsted sø and Gyrstinge sø as supplementary sources to the groundwater supply.

The present groundwater abstraction for irrigation purposes is rather limited, but the interest among farmers has increased. Especially the 1975-76 drought gave rise to a boom in licence-applications. Irrigation based directly on surface water resources is very limited and will not be permitted in the future, due to extreme low flow conditions during the irrigation season.

There are great recreational and conservation interests attached to the area. Especially the largest lake in the Suså-catchment, Tystrup sø and its surrounding area is a site of great concern. The streams within the basin are in general also subject to public awareness in terms of both their quantity and quality.

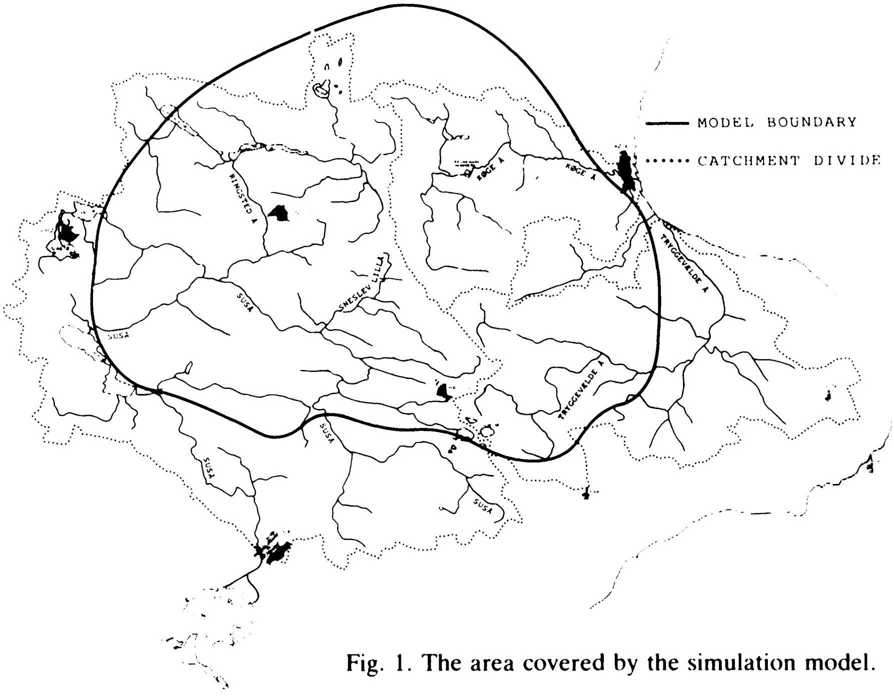


Fig. 1. The area covered by the simulation model.

The Suså as well as its tributaries act as recipients for municipal sewage. The waste water treatment plants operate on different treatment levels, but except from some minor plants with only mechanical treatment, the plants provide at least biological treatment.

In the following the combined hydrological/water quality model is briefly described along with a presentation of the results obtained from several hypothetical simulations in order to illustrate the applicability of the model.

The Combined Simulation Model

The simulation model consists of a number of hydrological and water quality submodels. The model aims at simulating the integrated effects of selected schemes for ground- and surface water abstractions, irrigation permissions, low flow augmentation and waste water treatment and discharge.

The superior configuration of the model system is shown in Fig. 2. The model operates on a daily basis using meteorological data comprising precipitation, potential evapotranspiration and mean temperature as input values. As part of another subproject a meteorological time series covering the period 1950-80 was established. This allows the consequences of given dispositions to be assessed under varying climatic conditions.

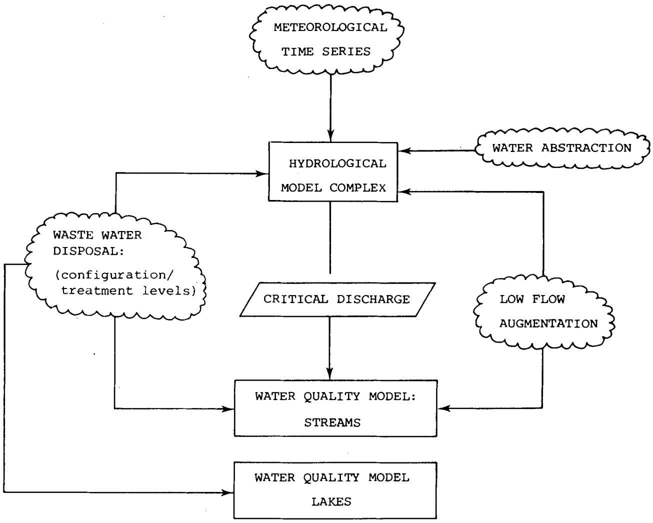


Fig. 2. The superior configuration of the simulation model.

The main component of the hydrological model complex is an integrated ground- and surface water model (Refsgaard and Hansen 1982). On a daily basis this model calculates the piezometric head in the primary artesian aquifer and the surface water runoff at arbitrary sites along the water courses. The reference mentioned above gives a detailed description of the model (appearing in this issue).

The northern part of the Suså-catchment comprises two regulated lakes, Haraldsted sø and Gyrstinge sø. The intake for the surface water withdrawal is located in Haraldsted sø, see Fig. 3. The two reservoirs, however, are connected by a pressure pipe in order to make a joint operation possible.

The inflow to the lakes is strongly influenced by the groundwater abstraction in the catchment. Taking this into account a water balance model for the lakes has been coupled to the ground and surface water model, thereby enabling the consequences of a conjunctive ground- and surface water abstraction to be assessed.

A similar water balance and reservoir operation model for Tystrup sø is also included in order to evaluate the possibilities for an increased surface water withdrawal from the area. The model assumes that the supplementary water developed by a possible regulation of Tystrup sø is carried to the existing reservoir-system (Gyrstinge sø – Haraldsted sø) partly by pipeline and partly through the stream Frøsmose Å. This allows the total surface water withdrawal to pass through the present intake in Haraldsted sø. Different strategies for the water transfer can be taken into account.

Furthermore, the hydrological model complex comprises crop specific root zone models in order to evaluate the hydrological consequences of irrigation on

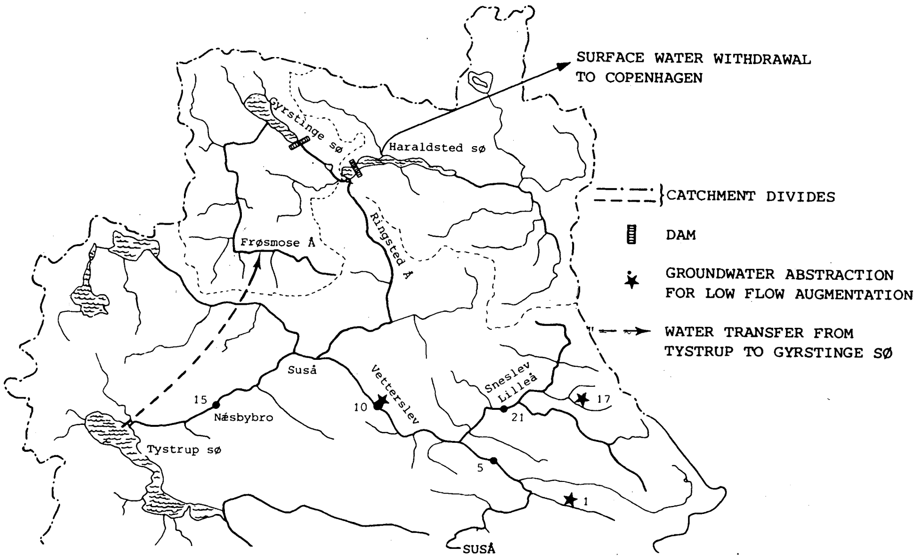


Fig. 3. The northern part of the Suså-catchment.

the poorest soil type in the area. Such models were developed for grass, barley, wheat and beets, taking into account individual characteristics, such as leaf area index and root depth.

The models enable different irrigation policies to be applied. A policy defines the area and the crops to be irrigated, the soil moisture content at which irrigation is initiated, the amount applied each time and some possible superior limitations of the overall irrigation.

The root zone models calculate the changes in evapotranspiration and percolation to secondary aquifers due to the irrigation. The water for irrigation purposes is assumed to be pumped from the primary artesian aquifer. Because the groundwater model is a Tyson-Weber type, where the horizontal water movement is supposed to take place between a great number of polygons, the potential irrigation area is specified as a subset of these polygons as shown in Fig. 4.

In Fig. 3 three sites for possible low flow augmentation are shown. The augmentation is based on groundwater pumped from the artesian aquifer and discharged directly into the stream. The consequences for the stream of a low flow augmentation scheme can hereby be investigated in terms of both its quantitative effects (net increase of runoff during pumping, and reduction in the subsequent period) and its quality effects (see below).

The user defined input to the water quality model complex comprises the waste water treatment at each of the treatment plants and the system of interceptor pipes. On basis of the prognosis for future waste water amounts the loads of

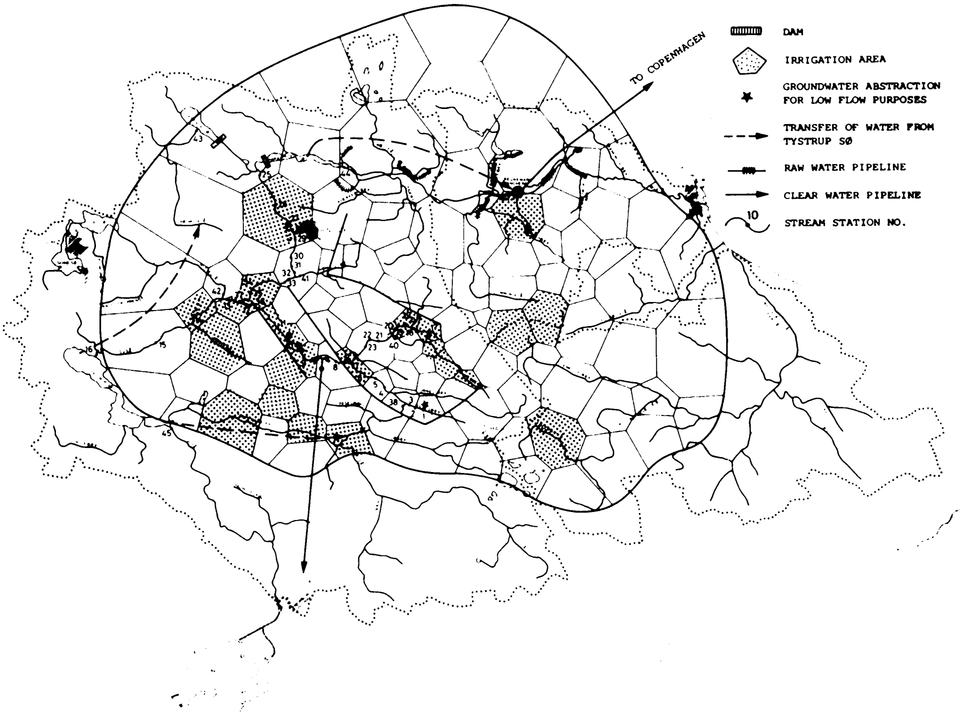


Fig. 4. Model area and dispositions to be specified by the user.

different pollutants is calculated by the model. Both the quality (concentrations of pollutants in the treated water) and the quantity (the forecasted discharge from the plants) are taken into account.

Nutrients are carried to the streams from both point sources (mainly phosphates from the treatment plants) and diffuse sources (mainly nitrates from the farmland). With these loads as input a simple mass balance model accounts for the load of nutrients on the lakes. By means of calibrated entrophication models (Nyholm 1977), relations between the nutrient load and the primary production have been established. These relations have been included in the model complex, thereby allowing for an evaluation of the water quality in the lakes, due to specific waste water treatment schemes.

The water quality model for the streams simulates the water quality during a critical period of the year. In the study this has been taken as the day when the minimum discharge appears, since the discharge is supposed to be a crucial factor in relation to the oxygen conditions. The critical discharge is determined by the hydrological model complex with due consideration to conjunctive ground- and surface water abstractions, irrigation and augmentation schemes, linking the two model complexes together as sketched in Fig. 2. The critical water quality condition is simulated in Suså from the tributary Gillesbækken to Tystrup sø and in the

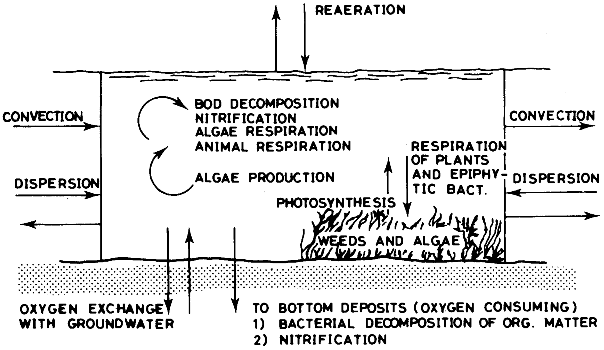


Fig. 5.
Processes in streams influencing the oxygen concentration.

tributaries Sneslev Lilleå and Ringsted Å, see Fig. 3. The water quality parameters are the content of organic matter (BOD) and the oxygen concentration. The applied water quality model (Dahl-Madsen and Simonsen 1974) takes into account a number of oxygen consuming and producing processes such as plant respiration and photosyntesis, decomposition of organic matter, nitrification of ammonia and reaeration from the atmosphere. The processes are sketched in Fig. 5.

The practical use of the combined simulation model is shown in Fig. 6. The dispositions of the water resource to be analysed are specified by the user as input to the model. This input comprises information on a) the water supply scheme, i.e. the groundwater abstraction distributed on polygons plus the strategy for reservoir operation; b) irrigation permissions, i.e. the irrigated area, its crop distribution and the applied irrigation policy; c) a waste water scheme, i.e. the interceptor network, the load and the treatment level provided at each treatment plant; and finally d) the strategy for low flow augmentation.

The output provided by the model comprises hydrological consequences on a daily basis in terms of for example the soil moisture content of irrigated and non-irrigated areas, the stream flow at user defined locations, reservoir contents and

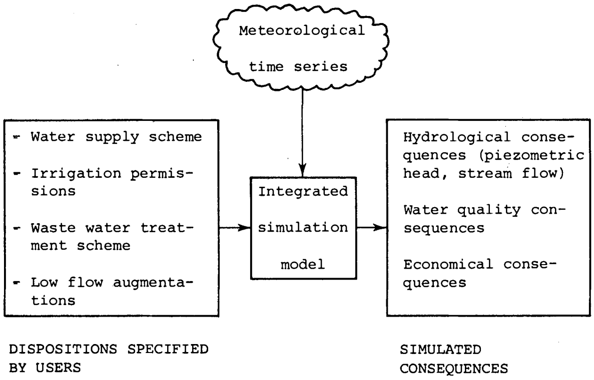


Fig. 6.
Use of the simulation model.

the piezometric head of the artesian aquifer in each polygon. For each year being simulated the model further provides information on the annual primary production in the lakes and the BOD and oxygen variations during the critical day at different stations along the water courses. Finally, the model offers an estimate of the annual costs associated with the specified waste treatment scheme.

Examples of Model Simulation

In the following the use of the model is exemplified by simulating the effects of hypothetical water resources dispositions. Besides the user-defined input the simulations are based on a 31-year meteorological time series covering the period 1950-80.

Increase of Surface Water Withdrawal

Some 10 years ago the city of Copenhagen carried out a series of pre-investigations in the Suså-catchment, in order to obtain a license for a considerable expansion of the groundwater abstraction in the area for water-supply purposes. Due to a weaker increase in water consumption than forecasted at that time, the application was never worked out in detail. However, the plan was one of the reasons for choosing the Suså-catchment as research area, and in the management part of the project it was therefore an interesting feature to investigate the consequences of an expansion of the water export from the catchment.

Because another study (Refsgaard and Stang 1981) has shown that a considerable increase of groundwater abstraction from the basin results in a serious decrease of the minimum discharge in the streams this specific possibility was not taken into account. As a possible alternative, an extended surface water withdrawal was examined by including Tystrup sø, see Fig. 3, as a surface water reservoir. Paying due attention to the great recreational value of the lake, only a moderate regulation was considered.

The inclusion of Tystrup sø in the reservoir system increased the total reservoir volume from 11 to 19 mill m^3, and a sequent peak analysis showed that in the hypothetical case, where all lakes in the basin were acting as one single reservoir, the safe yield could be expanded from 7.6 mill m^3/year to 19.5 mill m^3/year.

Depending on the applied strategy for the transfer from Tystrup sø to Gyrstinge sø, the actual withdrawal will approach more or less the theoretical maximum. Applying the strategy for transfer, as given in Fig. 7, the possibilities for withdrawal of 18 mill m^3/year were investigated. The simulations showed than only once in the 31-year period a deficit appeared, amounting to 1.7 mill m^3.

In the case of an actual implementation, more simulations are needed to unveil the trade-off between cost of transfer facilities and risk of shortage.

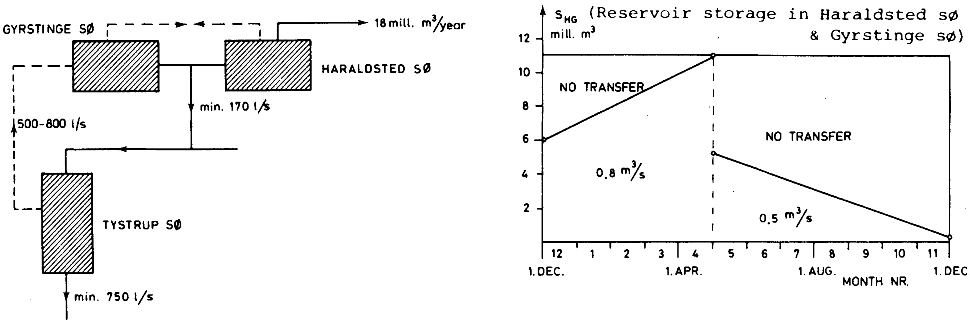


Fig. 7. Strategy for transfer of water from Tystrup sø to Gyrstinge sø and transmission intensities.

Conjunctive Abstraction of Ground- and Surface Water for Export Purposes

Assuming that a regulation of Tystrup sø could not be permitted, an alternative scheme providing 18 mill m^3/year (as above) was considered. Because the safe yield of Haraldsted and Gyrstinge sø only amounts to 7.6 mill m^3/year, a conjunctive utilization of ground- and surface water resources is necessary in this case. The increased groundwater development was established by assuming an intensified abstraction from boreholes, presently supplying the Regnemark waterwork, see Fig. 8. A time dependent strategy for the division between surface- and groundwater abstractions was applied, see Fig. 9, with the intention of keeping the supplementary groundwater abstraction as small as possible.

The simulation results showed that the supplementary groundwater abstraction necessary for safely increasing the supply with 10.4 mill m^3/year amounted to 2.9 mill m^3/year on the average. However, as seen from Fig. 10, large variations from year to year occured. As an example of the effects on the piezometric head of the primary aquifer at a location near the boreholes, histograms for the head are compared in case of the conjunctive abstraction in question and some reference

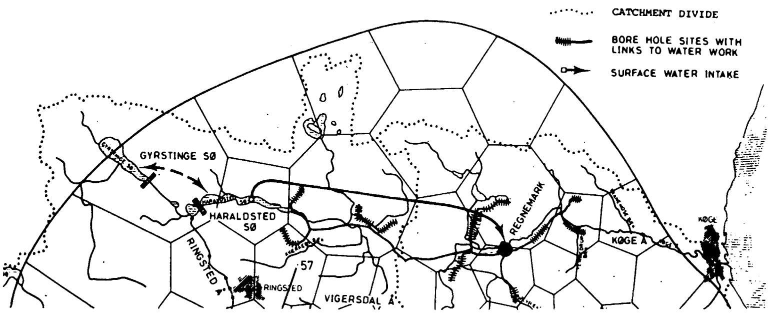


Fig. 8. Conjunctive surface- and groundwater abstraction.

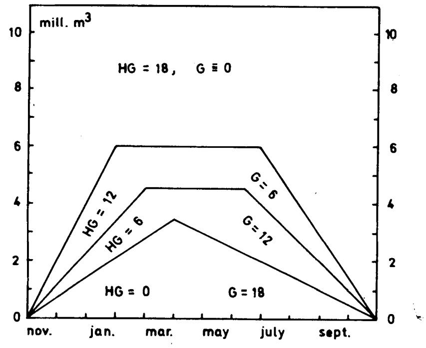


Fig. 9. Time dependent strategy for surface- and groundwater abstraction.

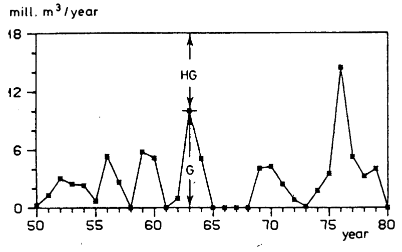
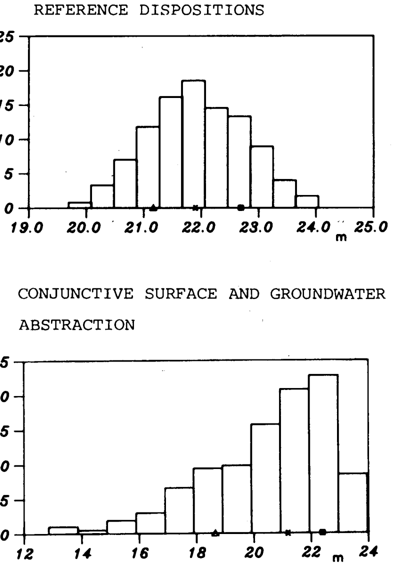


Fig. 10. Simulated surface- and groundwater abstraction 1950-80.

dispositions, respectively. The periodic groundwater abstractions with high intensity may cause severe depletion of the head, but as seen from Fig. 11, this is a rather seldom event. The median value only decreases approximately 1 m, and it should further be mentioned that the primary aquifer is relatively unaffected in some distance from the abstraction area, indicating negligible effects on the


REFERENCE DISPOSITIONS

CONJUNCTIVE SURFACE AND GROUNDWATER ABSTRACTION

Fig. 11.
Histograms for head of primary aquifer in polygon no. 57 (south of Haraldsted sø)

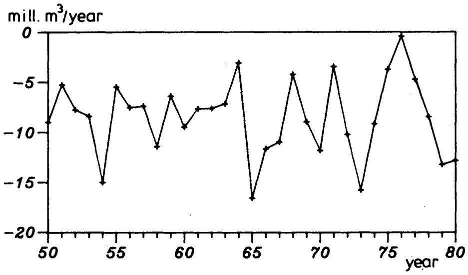


Fig. 12. Change of the runoff at Næsbybro in case of conjunctive abstraction of surface- and groundwater.

minimum streamflow in Suså.

The total expansion of water supply amounts to 10.4 mill m^3/year, while the decrease of the runoff at Næsbybro, see Fig. 3, only shows an average decrease of 8.5. mill m^3/year (with large variations from year to year), see Fig. 12. This difference is explained by the fact that groundwater abstraction at the Regnemark boreholdes causes groundwater inflow from the adjacent catchment, and thereby reduces the runoff here with the remaining 1.9 mill m^3/year.

The conclusion of this investigation is that 18 mill m^3/year could safely be developed by a combined ground- and surface water scheme. Hereby it is possible to preserve Tystrup sø as a conservation area, and the combined scheme can be operated so the minimum discharge in the area remains practically unaffected.

Irrigation

The effects of allocating water resources to irrigation purposes were investigated, partly by the crop specific root zone sub-models, and partly by the whole simulation model.

As an example of the results obtained by running the root zone model Fig. 13 shows the effects of grass irrigation during the years 1972-76. The applied policy prescribed irrigation of 40 mm every time the soil moisture content dropped below 50% of the maximum accessible during the irrigation season. In Fig. 13 the variation of the water content in the root zone in case of irrigation is compared to the variation in the case without irrigation. Below is shown the increase of the evapotranspiration and the percolation (negative values), respectively.

It is seen that the water demand of water for irrigation shows large variations from year to year. Further it is observed that the increase in evapotranspiration is dominating during the growth season, while the increase in percolation is prevailing in the succeeding period. By this and corresponding simulations it was found for practical irrigation policies that on the average approximately 50% of the total amount transpirates, while the remaining 50% percolates.

The effects of the irrigation on the streamflow, in case of irrigation of 63 km^2 within the catchment, was analysed by means of the total model. According to Fig. 14 it was found that the irrigation causes small absolute reductions of the

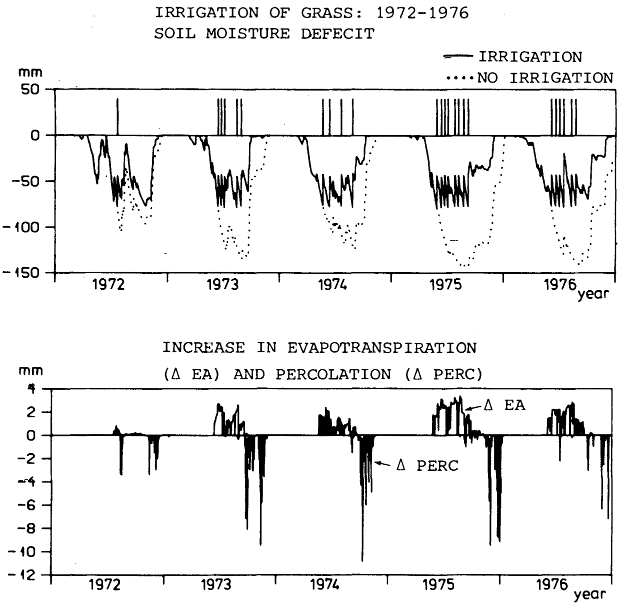


Fig. 13. Irrigation of grass 1972-76.

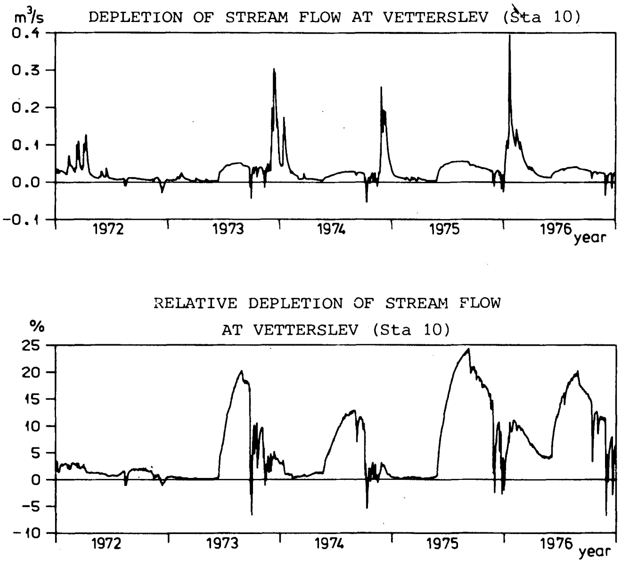


Fig. 14. The effects on streamflow in Suså at Vetterslev, due to irrigation 1972-76.

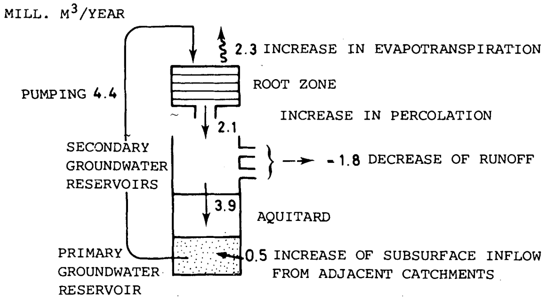


Fig. 15.
Average effects on the water balance of irrigation of 63 km^2 in the Suså-catchment.

streamflow during the summer period at the location Vetterslev (see Fig. 3). Relatively, however, the reductions can be significant due to the very limited streamflow in the summer period. The water quality effects were found to be negligible.

The groundwater abstraction due to irrigation varied between approximately 0 and 10 mill m^3/year with an average value of 4.5 mill m^3/year. The simulated average effect of the irrigation on the water balance of the Suså catchment is shown in Fig. 15.

Low Flow Augmentation

Use of groundwater for low flow augmentation purposes has not yet been applied in Denmark. This may be due to the fact that the consequences have not been sufficiently analysed. However, a simulation model of the present type may provide part of such an analysis. As an example, results are shown of implementing low flow augmentation from the three abstraction locations, station Nos. 1, 17 and 10, shown in Fig. 16, and controlled by the discharge at the stations Nos. 5, 21, and 10. The strategy for augmentation is given in Table 1.

The effect on the discharge at Vetterslev (station No. 10) is shown in Fig. 17. The figure shows how the pumping is controlled during five years. The variations of the net gain for the same five years are also shown together with the resulting changes of the discharge. It is seen that the required increase of the discharge is obtained during the pumping periods on account of a decrease of the ample

Table 1 – Strategy for low flow augmentation

Station No.	Pumping intensity m^3/s	Number of days with pumping	Control station	Critical discharge m^3/s
1	0.100	10	5	0.250
17	0.100	10	21	0.050
10	0.150	10	10	0.400

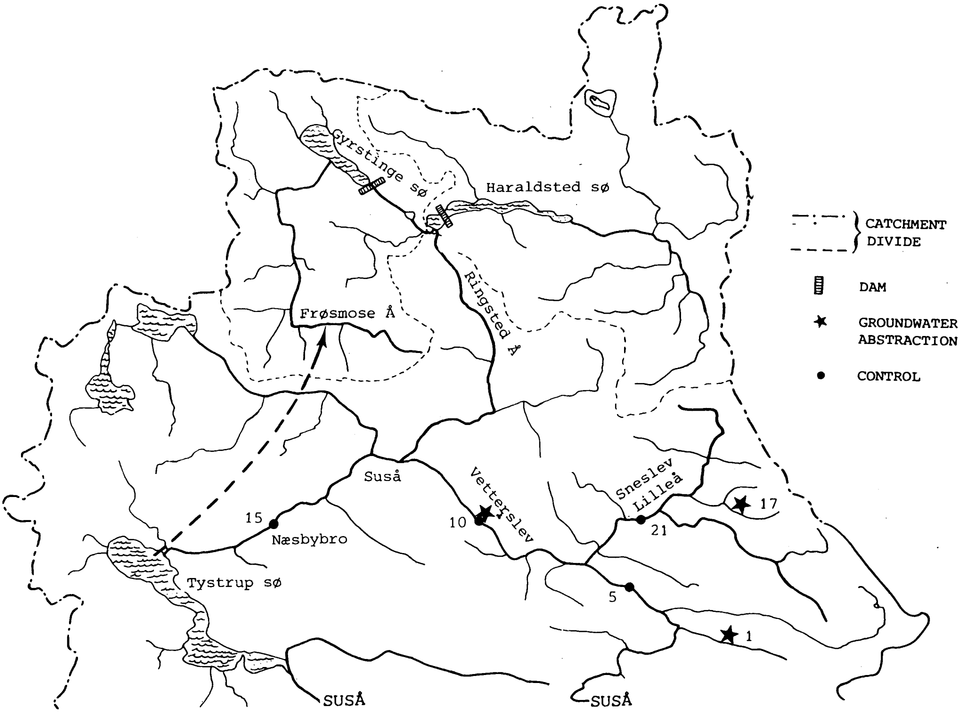


Fig. 16. Groundwater abstraction sites for low flow augmentation purposes and locations of control stations.

discharge during the winter season.

The augmentation scheme was combined with an alternative waste water treatment scheme. Compared to the standard scheme, the alternative one is much more decentralized and with less advanced treatment levels. Hereby a considerable reduction of the costs was obtained without remarkable effects on the water quality. The low flow augmentation scheme implied a considerable improvement of the water quality in the small tributary stream Sneslev Lilleå (see Fig. 2), while the conditions in the main course of the Suså system and in the lakes only slightly were influenced. The quality of the streams in terms of minimum concentrations of dissolved oxygen during the critical day is shown in Fig. 18, where the numbers at the abscissas axis are referring to stations along the water courses.

The simulations indicate that low flow augmentation can be a very effective measure of providing adequate streamflows – not only during severe drought periods, but it might also be used more regularly to increase the discharge during summer time. Besides these quantitative effects, improvement of the critical water quality conditions is expected as well.

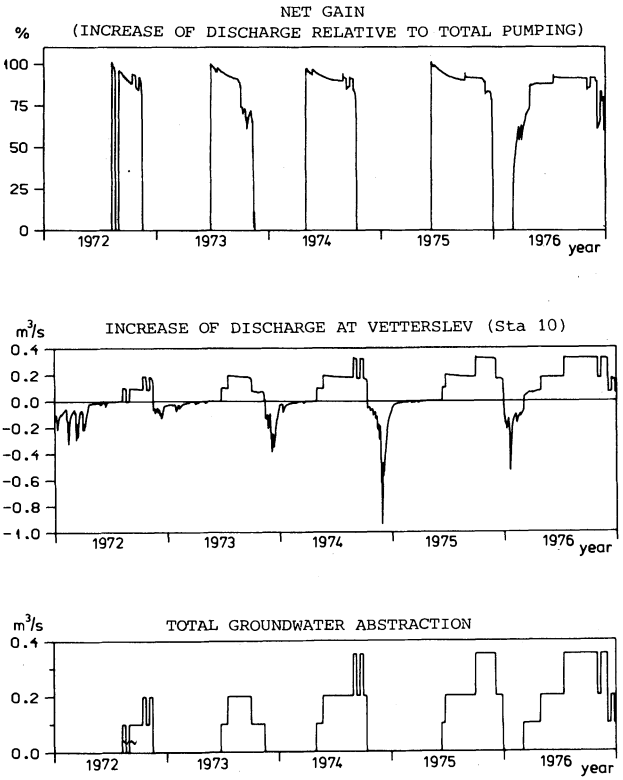


Fig. 17. Groundwater low flow augmentation 1972-76 and the effects on the discharge at Vetterslev (station 10).

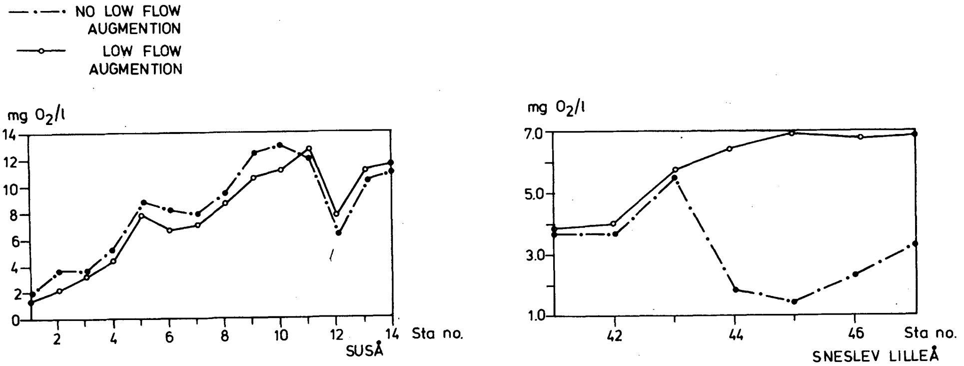


Fig. 18. Minimum values of disolved oxygen in Suså and Sneslev Lilleå with and without low flow augmentation.

Conclusions

A number of different interests are competing in the use of the water resources. The recognition of their mutual dependency is crucial to ensure an overall coordination of the water resources utilization. Further, this recognition is indispensable for providing a sound basis for political decisions on future water resources developments.

The study presented herein illustrates that it is possible to establish a unified system of models, enabling multiple effects of water resources dispositions to be analysed. By employing such models to assess hydrological –, water quality – and economical impacts of different alternatives, the information basis for the final decisions can be substantially improved.

References

Dahl-Madsen, K.I., and Simonsen, J. (1974) Water quality stream simulation. Research report from the Danish Water Quality Institute, ATV and the Dept. Sanit. Engng., Tech. Univ. of Denmark. (In Danish).

Nyholm, N. (1977) A Simulation Model for Phytoplankton Growth and Nutrient Cycling in Eutrophic, Shallow Lakes. *Ecological Modelling, 4* (1978) pp 279-310.

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

Refsgaard, J.C., and Hansen, E. (1982) A distributed groundwater/surface water model for the Susâ-catchment. Part I: Model description. *Nordic Hydrology, Vol. 13,5.*

Received: 22 October, 1982

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

Danish Hydraulic Institute,
Agern Allé 5,
DK-2970 Hørsholm,
Denmark.