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Low Flow Estimation and Hydrogeology in a Chalk Catchment

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Procedures to estimate low flow statistics at ungauged sites and their relation to hydrogeology are presented. The discussion is based on an example of a Danish chalk catchment of 242 km^2, within which the climatic variation is small compared to the physiographical variation. The spatial and temporal variation of streamflow was studied using synchronous discharge measurements and the application of a numerical model. The synchronous discharge measurements showed the runoff is unequally distributed within the catchment and depends primarily on the regional hydrogeology, but also on the lithology of the valley deposits. The numerical model was used to obtain an understanding of the hydrogeological effect on the temporal variation of the runoff from small subcatchments. This was not possible from the discharge measurements because of the high uncertainty of estimating the difference in flow between two nearby gauging stations. The temporal variation was found to be strongly related to the hydraulic gradient along the river. A knowledge of catchment processes and variability of runoff from modelling studies is shown to assist in low flow estimation.

Introduction

In recent years conflicts of interest between different uses of stream water during low flow periods (recreation, fishing, abstractions *etc.*) have increased the need for insight into the interaction between groundwater and streamflow, and for operational tools for making rational decisions about the groundwater exploitation.

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Setting up a full-scale coupled groundwater/streamflow model usually exceeds available resources of man power and data. Therefore, in practice, permission to abstract groundwater is often based on estimates of low flow statistics.

A widely applied technique to obtain estimates of flow statistics at ungauged sites is regional analysis, which is concerned with defining flow variability in space. Traditionally, there is a fundamental split between regional analysis and process studies. The work described in this paper can be seen as an attempt to diminish the gap between the two.

Regional analysis relates streamflow statistics at gauging stations to the physical and climatic characteristics of their drainage basins. These characteristics can also be obtained from the ungauged stream basins and thus, based on the regional relations, the flow statistics at the ungauged sites can be estimated. The regional relations are usually derived using multiple regression based on climatic and topographic parameters such as mean annual rainfall and basin area. Results obtained by regionalizing flood peak characteristics and mean flow are generally more accurate than low flow statistics (Riggs 1990).

Low flow statistics are highly dependent on the hydrogeology, and attempts to include geological information in regional studies were made by Gustard *et.al.* (1992) and Arihood *et.al.* (1991). However, because of the often complex relationship between physiography and baseflow the estimate is improved considerably by measuring the flow at the ungauged site at a time when the flow is low, and relating this to the recorded flow at a nearby gauging station (Riggs 1972; Krasovskaia and Gottschalk 1989). The discharge measurements can be made at many sites in the same basin on the same day, which is referred to in the literature as synchronous discharge measurements (Nielsen 1980), campaign measurements (Krasovskaia and Gottschalk 1989) or as seepage runs (Riggs 1972). The accuracy of the estimate of the low flow statistics is increased by repeating the discharge measurements at different flows. We can thus list three methods to estimate low flow statistics at ungauged sites in the order of increasing accuracy of the estimates:

The first method uses no discharge measurements and is based on an assumed relation between the flow at a nearby gauging station and the flow at the ungauged site. A simple assumption is a spatially uniform distribution of flow which allows the low flow statistics to be adjusted by the topographic catchment area.

The second method uses one discharge measurement at the ungauged site and relates the measured flow to the flow at a nearby gauging station. If the flow at the gauging station is equal to the low flow statistics, then no adjustment of the measured flows is necessary. If the flow at the gauging station is different from the low flow statistics, then the measured flow at the ungauged site must be adjusted. A simple way is to adjust the flow at the ungauged site using the same correction factor as for the gauging station. This assumes the temporal variation of flow is the same in per cent for all catchments.

The third method uses more than one discharge measurement at the ungauged

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site. Based on the measured discharges a relationship between the flows at the ungauged site and a nearby gauging station is assumed. A widely used assumption is a linear relationship on a log-log plot (Riggs 1972).

This paper discusses the former two methods in relation to the hydrogeology using the example of a 242 km^2 Danish chalk catchment. The hydrogeological influence on the low flow can be studied because the climatic variation is small, the lake area is only 0.1 % of the catchment area, and artificial influence on streamflow is negligible. The catchment is gauged at the outlet and a typical problem is to extrapolate the low flow statistics for this station, which represents an average of the entire catchment, to subcatchments (< 20 km^2). The work highlights the problem of interpolating from large gauged catchments to smaller ungauged subcatchments (Krasovskaia and Gottschalk 1989).

For this study the synchronous discharge measurements were carried out ten times in order to estimate the spatial variation of low flow using the third method. The results showed a great spatial variation in runoff due to the hydrogeological variability. It was not possible to estimate the temporal variation of runoff in small subcatchments on the basis of the measurements because of the limited accuracy of differences in flow measurements of two nearby sites. Therefore a numerical groundwater model was applied to the study catchment in order to investigate the hydrogeological response on the temporal variation of runoff. This approach makes it possible to use the knowledge of the hydrogeological characteristics of the catchment when determining the variation of low flows.

Hydrogeological Setting of the Alling Catchment

The Alling catchment is located in the eastern part of Jutland in Denmark (Fig. 1) with altitudes ranging from 3 to 117 m. The landscape is a result of quaternary glacial processes, as well as of pre-quaternary processes such as the development of a deep (2-3 km) salt dome (Madirazza 1986) which forced up the overlying geology including the chalk from the Cretaceous and the Danian chalk from the Tertiary. The chalk forms the primary aquifer, and at the centre of the dome, which is also the centre of the catchment, the chalk surface is 30-40 m above sea level and very close to the surface (Fig. 1). In the western and southern areas, the Danian chalk is overlain by almost impermeable Tertiary clay with a thickness of up to 50 m near the topographic divide.

On top of the chalk are quaternary deposits of till clay and glaciofluvial sand (Fig. 2). The cover is thin in the central areas and even in the shallow Skader and Rosenholm valley. However, in the broad and deep Alling valley the quaternary deposits reach thicknesses of 50 m. The lithology of the quaternary deposits in the valleys determine the hydraulic contact between the regional aquifer and the streams. Fig. 3 shows the valley deposits dominated respectively by till clay and by

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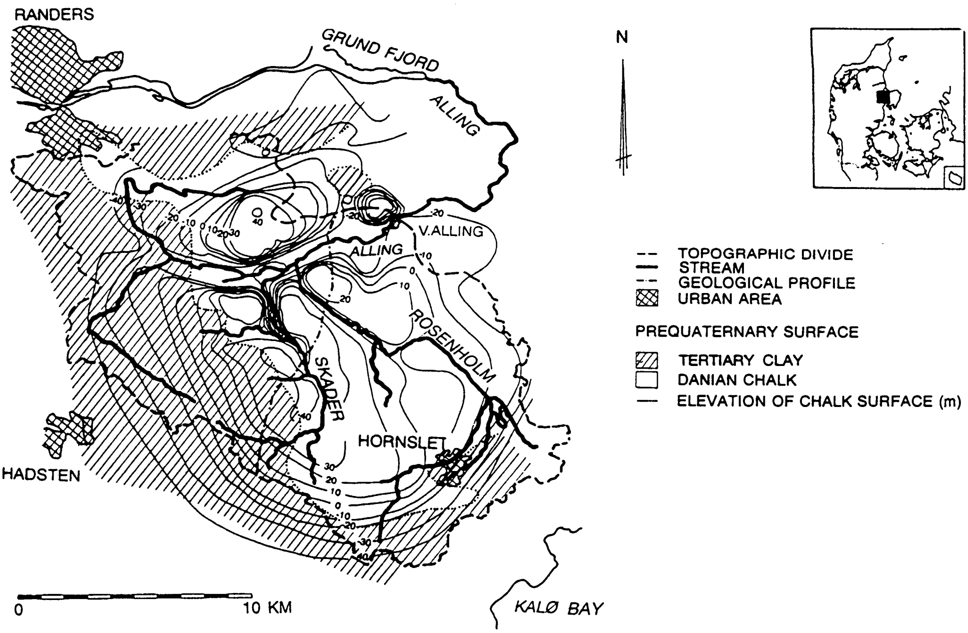

Fig. 1. The pre-quaternary surface in the Alling catchment.

sand. All geological information has been derived using records from about 200 wells shown in Fig. 3.

The map with the hydraulic heads in the regional aquifer (Fig. 4) was based on water level observations in the 200 wells shown in Fig. 3. Most observations were made in 1988, and the annual variation was found to be less than one metre in the confined areas and only a few metres in the unconfined areas. The head (> 60 m) and the hydraulic gradient are high in the south-western area, while in the northern and eastern areas the head (< 20 m) and the hydraulic gradient are low. The aquifer is unconfined in the central areas where the chalk has the maximum elevation (Fig. 1). The hydraulic head is strongly influenced by the Alling and the

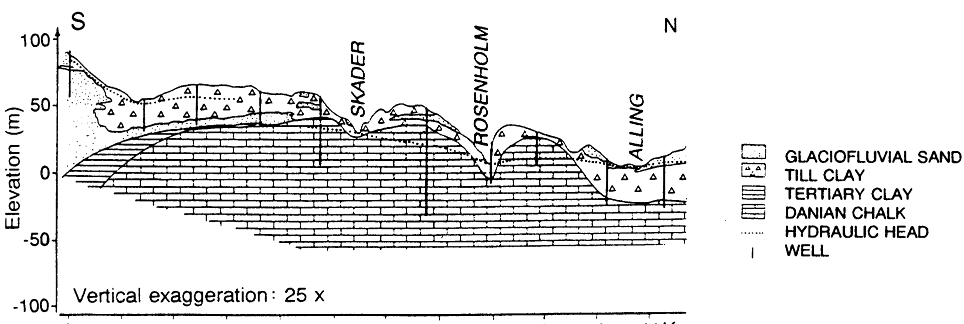

Fig. 2. Geological profile across the Alling valley. Location shown in Fig. 1.

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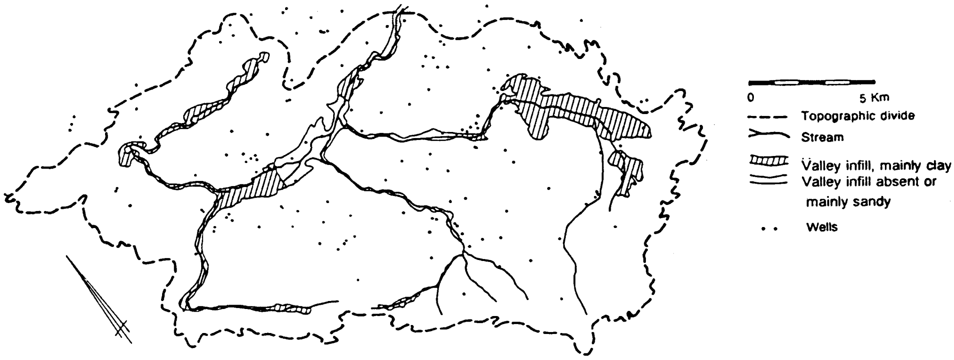

Fig. 3. The lithology of the quaternary valley deposits and the location of wells.

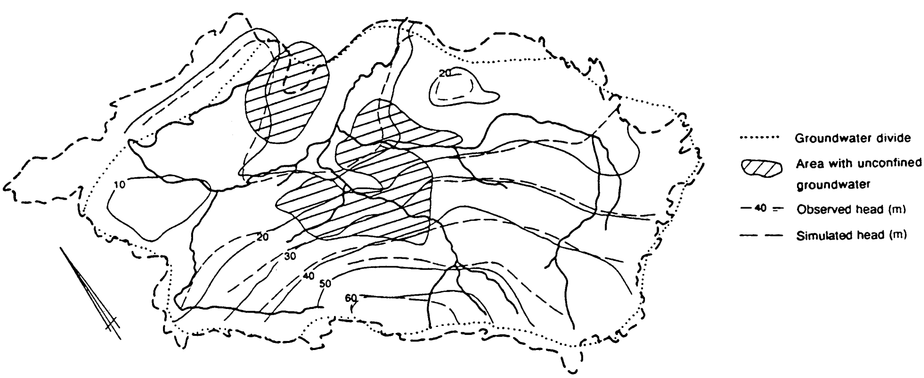

Fig. 4. The observed and simulated hydraulic heads in the regional aquifer. Areas with unconfined groundwater are shown.

Rosenholm valleys, while the Skader valley does not affect the head significantly. The groundwater catchment is about 10 % smaller than the topographic catchment.

The spatial variation in mean precipitation and actual evapotranspiration was found to be low within the catchment (Clausen 1989). The actual evapotranspiration and the infiltration from the root zone were calculated using a distributed root zone model where the root zone capacity was based on soil type and vegetation according to Madsen and Platou (1983). The average values of the climatic parameters and the mean gauged flow per unit area are given in Table 1. The small difference between the infiltration from the root zone and the runoff is due to subsurface runoff and pumping. The recharge to the chalk is greatest in the central areas where only a thin till covers the chalk. The transmissivity and the storativity varies in the aquifer. Results of pumping tests showed a range in transmissivity from 1.1×10^{-3} m^2/s to 50×10^{-3} m^2/s (Clausen *et.al.* 1992). The storativity in the unconfined part of the aquifer was estimated as 3.5 % (Clausen 1989).

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Table 1 – Average values in mm of precipitation P, potential and actual evapotranspiration, PE and AE, the infiltration from the root zone I, and the mean gauged flow per unit area, Q, of the Alling catchment for the period 1974-1988.

Area (km^2)	Period	P	PE	AE	I	Q
242	1974-1988	712	556	467	245	233

The Spatial Variation of Low Flow

In the Alling river system two gauging stations (Fig. 5) were in operation during the years 1978-1988, the one in the Alling (site No. 1) which gauges the whole catchment, the other in the Brusgaard tributary (site No. 41). The daily time series were derived from continuous water level records. The transformation of water levels to daily flows were based on monthly discharge measurements using current meters. The other sites marked and numbered in Fig. 5 are ungaged sites where synchronous discharge measurements using current meters were carried out once in 1975 by the Danish Land Development Services, and up to ten times during the period 1987-89 by the authors.

Two low flow statistics for the two gauging stations were estimated on the basis of the daily time series records, these are the 95 percentile 1-day flow and the median of the annual 1-day minimum. The low flow statistics and the mean flow for 1974-1988 are given in Table 2. The figures show the flow per unit area in the Brusgaard catchment is approximately half of the average value for the whole catchment. Thus, if the flow in the Brusgaard catchment was estimated on basis of the catchment area only, it would be overestimated by approximately 100%.

The spatial variation of low flow statistics was estimated from the results of the

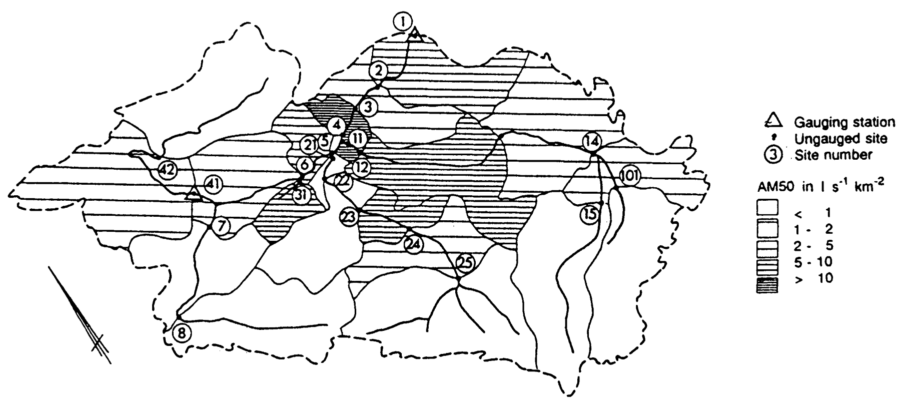

Fig. 5. The spatial variation of the estimated median of the annual minimum (AM50) of the flow per unit area in the Alling catchment.

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Table 2 – The mean flow (1974-1988), the 95 percentile 1-day flow (Q95) and the median of the annual 1-day minimum (AM50) for the two gauging stations in the Alling catchment.

River	Area km^2	Mean	Q95	AM50
			$l\ s^{-2}$ ($l\ s^{-1}\ km^{-2}$)	
Alling	242	2,024(8.36)	675(2.79)	532(2.20)
Brusgaard	39	176(4.51)	49(1.26)	40(1.03)

synchronous discharge measurements. The measured discharges for each site were plotted against the flows at the Alling gauging station, which were also measured using a current meter. The relationships for four sites are shown in Fig. 6. A regression line was fitted to the points for each site and the low flow statistics for the ungauged sites were calculated. The low flow statistics for the individual subcatchments were calculated as the difference between the estimated low flow statistics at two nearby sites divided by the subcatchment area.

Fig. 5 shows the estimated median of the annual minima. The values range from close to zero in the peripheral areas to more than 100 l s^{-1} km^{-2} around the confluence of the Rosenholm with the Alling. The spatial distribution reflects the topography and the hydrogeology including the recharge, which is highest in the central areas with unconfined groundwater (Fig. 4). The local variations are related to the distribution of permeable and semipermeable quaternary deposits in the river valley (Fig. 3) in that high runoff values are found around reaches dominated by sandy deposits for example in the Alling between sites 3 and 6, or where quaternary deposits are absent for example in the reach between sites 23 and 24 in the Skader.

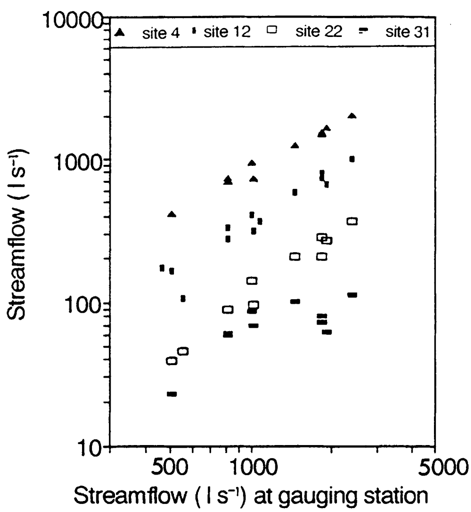

Fig. 6.

Relationship between the measured flows at four sites and at the Alling gauging station (site 1).

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These results highlights the problem with regionalization in that even local variations affect the low flows. In a catchment with a complex geology such as the Alling it is difficult to quantify the geological variation. It is therefore highly recommended to carry out at least one discharge measurement at the ungauged site. To adjust the measured flow to the low flow statistics it is important to understand the relation between flows at different sites.

The Relation between Measured Flows at Different Sites

The relation between the synchronously measured flows at the different sites and the measured flow at the Alling gauging station was studied using plots like the one in Fig. 6. The flows were also plotted using normal scales. Most points showed a linear relationship, but the points exhibited some scatter, especially at site 31 (Fig. 6). Because of the scatter which is probably due to uncertainty related to the discharge measurements, and the limited numbers of points, it was difficult to identify any deviations from linearity. In order to increase the number of points the simultaneously recorded daily flows at the two gauging stations in the Alling catchment were plotted against each other on a normal plot (Fig. 7). Only flows lower than the mean for the Alling are included. The points show a large scatter, and a slightly upward concave relationship. This is verified in Fig. 8, which shows the 1-day flow duration curves for the two gauging stations. The values for the Brusgaard are lower than in the Alling for flows lower than 40 % of the mean, but not for values higher than 40 %. This explains why the relationship shown in Fig. 7 is concave upward.

For linear relationships the slope of the curve describes how much the flow at

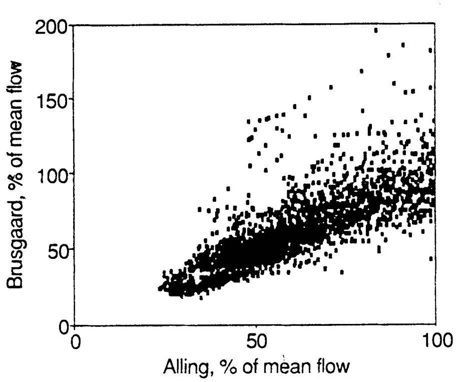

Fig. 7.
Relationship between the simultaneously recorded daily flows at the two gauging stations in the Alling catchment.

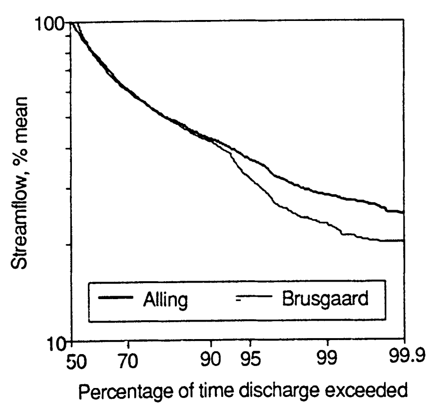

Fig. 8.
Flow duration curves for the two gauging stations in the Alling catchment.

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one station varies compared to the variation at the other station. This can then be used in the estimation of low flow statistics on basis of single measurements. However, it was not possible to estimate the temporal variation on the basis of the synchronous discharge measurements because of the errors in flow measurement. It was therefore decided to apply a numerical model to the primary aquifer to estimate the temporal variation of groundwater flow from small subcatchments.

The Temporal Variation of Modelled Groundwater Flow from Subcatchments

The regional groundwater flow was modelled for the years 1974-1988 using a numerical groundwater model. It is well known that flow in chalk is dominated by flow in fissures and fractures, but studies of the British Chalk, which is similar to the Danish, have shown the flow is dominated by laminar flow in fissures with an effective width of up to about 2 mm (Foster and Milton 1974; Connorton and Reed 1978). It is therefore reasonable to assume the applicability of Darcy's law on which the existing numerical models are based. The model used in this study was the Aquifer Simulation Model (ASM) developed by Kinzelbach and Rausch (1989). Other numerical models have been applied to chalk catchments, see for example Hansen and Dyhr-Nielsen (1982), Morel (1980) and Rushton *et. al.* (1989).

The flow was modelled using a grid size of either 250 or 500 m in both directions using a monthly time step. The boundary was defined as a non-flux boundary following the groundwater divide. The recharge to the aquifer took place as direct infiltration from the root zone in the unconfined aquifer (Fig. 4) and as leakage from the quaternary deposits in the confined aquifer. The water level in the quaternary deposits on the confined areas was assumed to be constant two metres below the surface. The flow to the streams in both the confined and the unconfined areas was defined as a constant named the stream coefficient multiplied by the head difference between the aquifer and the stream. The stream head (the water surface level) was assumed to be constant in time. The stream coefficient was estimated on the basis of the results of the synchronous discharge measurements and varied from 5×10^{-10} s^{-1} in the peripheral areas to 1×10^{-7} s^{-1} in the central area. The distribution agreed with Fig. 3 in that small values were found in valleys with clayey quaternary deposits.

The transmissivity, the storativity and the leakage coefficients were calibrated by comparing observed hydraulic heads (Fig. 4) with simulated heads obtained from steady state simulations, and by comparing observed flows including the results of the synchronous discharge measurements with the simulated flows obtained from transient simulations for 1974-1988.

The calibrated values of the transmissivity range from 0.2×10^{-3} m^2 s^{-1} to 50×10^{-3} m^2 s^{-1}. The lowest values are found close to the water divide in the South-Western

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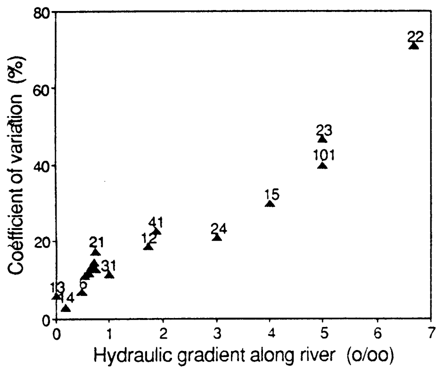

Fig. 9. The coefficient of variation of the modelled flow to river reaches as a function of the hydraulic gradient along the river. The numbers refer to the station at the downstream end.

area where no pumping test was made. Here, presumably, the Tertiary clay has protected the chalk against glacial erosion. The storativity was optimized to 3.5 % in the unconfined aquifer and 0.5 % in the confined. The leakage coefficient was optimized to $1\times10^{-9}\ s^{-1}$.

The groundwater flow to the individual reaches was found by summing the flows to all cells within the valley reach. The simulated flows at the gauging stations gave a good fit to observed flows lower than the mean, and therefore only these values were used to estimate the temporal variation. The temporal variation was found to be strongly related to the hydraulic gradient along the river (Fig. 9), which was estimated from the map showing the average hydraulic heads (Fig. 4). The highest variation was found in the Skader where frequent changes between effluent and influent flow situations occurred. The smallest variations were found in the middle reaches of the Rosenholm and the Alling. The results show that the hydraulic gradient along the river is a useful indicator of the temporal variation of low flows. This can be used when low flow statistics at ungauged sites are estimated on the basis of single discharge measurements.

Conclusions

The synchronous discharge measurements in the Alling catchment identified a great spatial variation of low flow. The low flow per square kilometre is highest (> 100 $l\ s^{-1}\ km^{-2}$) in the central catchment due to the topographical and geological variation, and close to zero in some of the peripheral areas. The lithology of the quaternary deposits in the river valley was also found to be important for the flow distribution. In a catchment such as the Alling it is difficult to quantify the geological variation in an index which could be used in regionalization. It is therefore

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strongly recommended to carry out synchronous discharge measurements for estimation of low flow statistics.

When low flow statistics are to be estimated on the basis of discharge measurements it is important to know the relationship between flows. The daily flows recorded at the two gauging stations showed a tendency for the Brusgaard to have a slightly higher variation at the lowest flows compared to the Alling. The temporal variations of low flow in all subcatchments were estimated using a numerical groundwater model, which was calibrated on the basis of observed groundwater heads and the results of the synchronous discharge measurements. The temporal variation was found to be dependent on the hydraulic gradient along the river. This parameter can therefore be considered as a key hydrogeological index in estimating low flow statistics at ungauged sites using single discharge measurements and comparison with nearby gauging stations.

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References

Arihood, L.D., and Glatfelter, D.R. (1991) Method for estimating low-flow characteristics of ungauged streams in Indiana, U.S. Geological Survey Water Supply Paper 2372, 18 p.

Clausen, B. (1989) Alling å-systemet. Grundvandsdannelse samt udveksling mellem grundvand og vandløb, in Danish (The River Alling. Groundwater recharge and the interaction between groundwater streamflow). M. Sc. thesis, Department of Earth Sciences, Aarhus University, Denmark, 122 p.

Clausen, B., Rasmussen, K.R., and Ovesen, N. (1992) The variation of baseflow from a Danish chalk aquifer, Nordic Hydrological Conference in Alta, Norway, NHP report No. 30, pp. 275-285.

Connorton, B.J., and Reed, R.N. (1978) A numerical model for the prediction of long term well yield in an unconfined chalk aquifer, *Quart. Journal of Eng. Geol., Vol. 11,* pp. 127-138.

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Foster, S.S.D., and Milton, V.A. (1974) The permeability and storage of an unconfined chalk aquifer, *Hydrol. Sci. Bull., Vol. 19, No. 4,* pp. 485-500.

Gustard, A., Bullock, A., and Dixon, J.M. (1992) Low flow estimation in the United Kingdom, Report No. 108, Institute of Hydrology, Wallingford, UK, 88 p.

Hansen, E., and Dyhr-Nielsen, M. (1982) The hydrological Susaa-study, *Nordic Hydrology, Vol, 13(5),* pp. 257-262.

Kinzelbach, W., and Rausch, R. (1989) Aquifer simulation model. User manual, 49 p.

Krasovskaia, I., and Gottschalk, L. (1989) Aspects of hydrological interpolation with the help of GIS, IAHS publ. No. 187, pp. 137-145.

Madirazza, I. (1986) The development of Salt Structures in the North Danish Basin, Geoskrifter 24, Aarhus University, pp. 225-233.

Madsen, H.B., and Platou, S.W. (1983) Land Use Planning in Denmark: The Use of Soil Physical Data in Irrigation Planning, *Nordic Hydrology, Vol. 14(5)*, pp. 267-276.

Morel, E.H. (1980) The use of a numerical model in the management of the Chalk aquifer in the Upper Thames Basin, *Quart. Journal of Eng. Geol., Vol. 13*, pp. 153-165.

Nielsen, S.A. (1980) Mapping of median minimum discharges in stream systems by means of synchronous flow measurements. 6th Nordic Hydrologic Conference, UNGI-rapp. 53, Uppsala, pp. 151-160.

Riggs, H.C. (1972) Low flow investigations, USGS Techniques of Water-Resources Investigations 4, B1, 18 p.

Riggs, H.C. (1990) Estimating flow characteristics at ungauged sites, IAHS publ. No. 191, pp. 159-169.

Rushton, K.R., Connorton, B.J., and Tomlinson, L.M. (1989) Estimation of the groundwater resources of the Berkshire Downs supported by mathematical modelling, *Quart. Journal of Eng. Geol., Vol. 22*, pp. 329-341.

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