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Discharge Data Collection and Analysis Strategies in Low Flow Studies

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The objective of this paper is to determine the most appropriate data collection strategy and analysis techniques which should be used to assess the low flow regime of a catchment. The data used were: a) synchronous discharge measurements during low flow periods, and b) continuous daily flow records. The analyses based on both types of data were able to distinguish different low flow regimes within a 114 km^2 Danish catchment. Despite the limited spatial variation in climate and geomorphology there was a high spatial variability in low flows caused by differences in the lithology of sediments. This demonstrates the difficulties in using simple indices of catchment geology in regional low flow estimation. The results highlight the benefits of using synchronous discharge measurements, both for estimating low flows at ungauged sites, and for understanding groundwater flow paths. Analyses of daily flow records from six gauging stations in the catchment showed that a baseflow index was more useful than the flow duration curve for classifying low flow regimes when only short records were available. The paper illustrates the importance of estimating the uncertainty of discharge measurements when interpreting low flow data.

Introduction

Low flow regimes can be described by a number of low flow measures. Commonly used measures are statistics derived from the annual minimum series (*e.g.* the mean annual 7-day minimum, Pearson 1995; the median annual 1-day minimum, Nielsen 1980; the 7-day 10-year minimum, Riggs 1985), and a given percentage exceedance from the flow duration curve (*e.g.* the 10-day 95 percentile discharge, Institute of Hydrology 1980). Other measures suggested are baseflow indices (Institute of Hydrology 1980; Nathan and McMahon 1990), and drought severity and duration based on the theory of runs (Yevjevich 1967; Dracup *et al.* 1980). These parameters are all derived from gauged flow records.

In areas without gauging stations low flow regimes can be identified by using discharge measurements, or by regionalization using regression equations (Riggs 1990). If many discharge measurements are carried out within a river network on the same day they are referred to as synchronous discharge measurements (Nielsen 1980), campaign measurements (Krasovskaia and Gottschalk 1989) or seepage runs (Riggs 1972). For both approaches an understanding of the interaction between geology and low flows will improve the accuracy of flow estimation at the ungauged site (Musiake *et al.* 1975; Clausen and Rasmussen 1993). Examples of the incorporation of hydrogeological characteristics in regionalization procedures were given by Simmers (1975), Arihood and Glatfelder (1986), Hayes (1991), Gustard *et al.* (1992), Demuth and Hagemann (1993) and Gustard and Irving (1993).

The objective of this paper is to determine the best strategy for discharge data collection and analysis for identifying low flow regimes within a catchment. The paper focuses on the analysis of two different types of data: synchronous discharge measurements, and daily flow records from gauging stations. Collection of both types of data require considerable hydrometric resources, the measurements being spread out in space using the former method, whereas the latter needs many measurements at the same site over many years. The analyses presented here were based on data collected in an experimental catchment in Denmark with a relatively large number of gauging stations. The paper discusses the advantages and disadvantages of using the two different types of flow data to identify low flow regimes, and relates these to catchment geology.

The Experimental Catchment

The Gjern catchment (114 km^2) is located in the eastern part of Jutland in Denmark (Fig. 1) and is representative of Danish catchments with regard to size and geology. The topography is relatively flat with elevations between 50 m and 100 m above Datum in about 80 % of the catchment. Only in and near the main valley is the elevation lower than 50 m with the lowest value at 19 m at the downstream gauging station. The highest elevations (above 75 m) are along the eastern and southern catchment boundary with a maximum at 139 m in the South. Most of the land (75%) is used for arable farming, 13% is forested, and the one lake in the catchment has an area of 0.35 km^2 (0.3 %). The precipitation is about 750-800 mm/year, and the evapotranspiration about 450-500 mm/year.

The geology is dominated by Quarternary and Tertiary sediments, which can be categorized into three general lithologies:

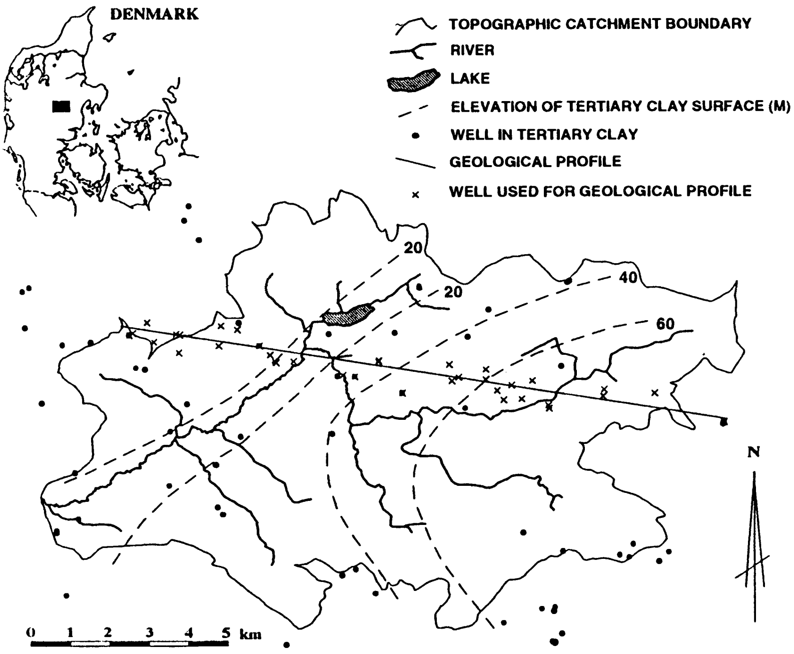

Fig. 1. The study area: the Gjern catchment in Denmark.

a) *Tertiary marine clays* are impermeable. Its surface (Figs. 1 and 2) forms a hydrogeological base from which only the main valley, the Gjern valley, can be identified.

b) *Sands* constitute the primary aquifer and are either Tertiary limnic mica sands, or glaciofluvial sands from the Quarternary. The thickness of the aquifer varies from a few metres to 50-60 m. The mica sands dominate in the western part of the catchment, and are locally interbedded with limnic silt and clay (Rasmussen *et al.* 1995).

c) *Till clays* cover the sand deposits in most of the catchment, and within the sand deposits there are also lenses of till clay. The top till varies in thickness from zero to about 30 m. The greatest thicknesses of till are found in the eastern part of the catchment (Fig. 2).

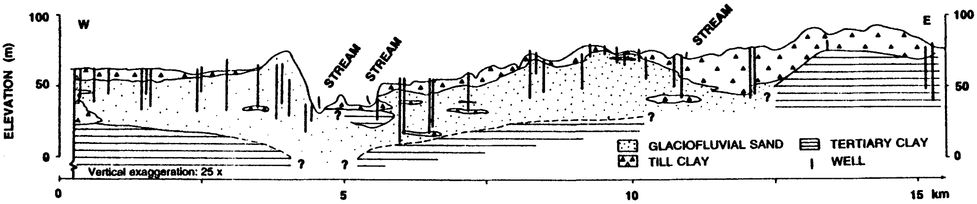

Fig. 2. Geological profile. The location is shown in Fig. 1.

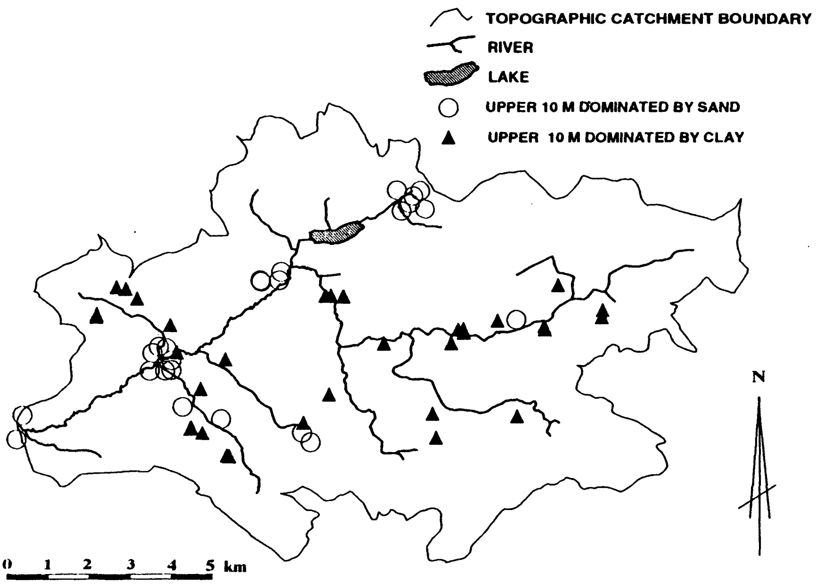

Fig. 3. The distribution of clay-dominated (more than four metres of clay in the upper ten metres) and sand-dominated (less than four metres of clay in the upper ten metres) riparian areas.

The lithology of the riparian deposits is of special interest for the baseflow distribution. Based on drilling journals all wells within 500 m of the river were grouped into two classes, one with less, and one with more than four metres of clay in the upper ten metres (Fig. 3). This classification indicates a difference between the Gjern valley and the other riparian areas. The riparian zones in the south-eastern areas are particularly noteworthy in that they are consistently dominated by clay.

Data and Methods

Synchronous Discharge Measurements

The usual approach is to carry out many discharge measurements in the same catchment in a dry baseflow period when water levels are almost constant (Nielsen 1980; Riggs 1985). This was done at up to 27 sites (Fig. 6) by using propellers, once in August 1976 (Danish Land Development Service 1976), once in June 1990 (Schmidt 1991), and once in June 1993.

Typical dimensions of cross sections in the main channel downstream site 5 were 5 m width and 80 cm maximum depth, and in the tributaries 1 m width and 30 cm maximum depth. The numbers of velocity measurement points were, in the former cross section about 40 (12-13 verticals, each with 2-4 points depending on the depth), and in the latter cross section about 20 (2-3 points in each of 7-8 verticals). The discharges were estimated by using the computer program CALQ (Clausen and Jensen 1994). This program uses a two-dimensional interpolation of the velocity, which is believed to give more accurate results for small rivers, instead of the traditional division of the cross sections into verticals. The discharges were used to calculate the specific discharge (*i.e.* the baseflow per unit area) for each subcatchment by subtracting the measured flow(s) at the subcatchment inlet(s) from the flow at the outlet, and dividing by the topographic subcatchment area.

To examine the uncertainty of the discharge measurements the flows at five sites during the 1993 campaign were measured twice, simultaneously, using different instruments and different, but nearby, river cross sections. The discharges of these measurements were estimated using both program CALQ and program VINGE (Erup 1976) which latter uses a traditional division of the cross section into verticals.

Gauged Flow Records

Daily streamflow data were available from six gauging stations (sites 1, 3, 9, 101, 401 and 602, Fig. 6) of which two were in operation from 1974, and the others in shorter, overlapping periods (Table 1). The data were made available by the National Environmental Research Institute and the Danish Land Development Service. The daily flows were estimated in the usual way (*e.g.* Shaw 1988) from stage records, and stage-discharge relationships calibrated with the aid of monthly discharge measurements using propellers. Because of the low number of common operation years (the four years 1986-1989, Table 1) it was decided to apply the following low flow measures based on daily values:

a) *The* 90 *and* 95 *percentiles* (*Q*90 *and Q*95) found from the flow duration curves for the period 1986-1989.
b) *Baseflow index* (BFI) found from a simple minima selection technique defined by the Institute of Hydrology (1980).

The BFI gives the ratio of baseflow to total flow and takes values between zero and

Table 1 – Gauged flow records in the river network of Gjern

Station number	1	3	9	101	401	602
Length of record (years)	19	4	6	5	10	19
Period of record	1974-92	1986-89	1984-89	1985-89	1983-92	1974-92
Mean flow (m^3/s):						
complete record	1.060	0.739	0.238	0.113	0.235	0.071
1986-1989	1.122	0.739	0.244	0.110	0.219	0.065

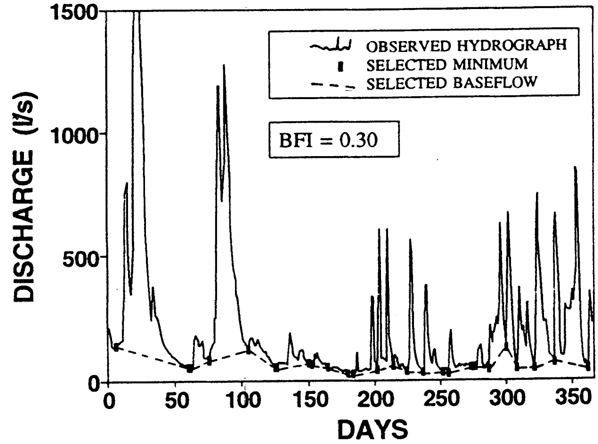

Fig. 4.
The hydrograph and the selected baseflow in 1986 at site 9.

one, see the example in Fig. 4. The BFI is found using the following technique (Gustard *et al.* 1992): First, the minima of 5-day non-overlapping periods are found from the entire record. Next, those minima which, when multiplied by 0.9, are less than the two adjacent minimum values are selected as the turning points. These are then connected by straight lines to form the baseflow hydrograph. If the calculated baseflow exceeds the recorded flow the baseflow is set equal to the recorded flow. The BFI is calculated as the area beneath the baseflow hydrograph between the first and the last selected minima, divided by the area beneath the corresponding recorded hydrograph.

It is clear that the method does not attempt to simulate the groundwater flow but rather to provide a simple and objective method to calculate an index related to baseflow response. Hutchinson (1983) found that the BFI for New Zealand rivers can be estimated with a standard deviation of 0.04 from only two years of data. The BFI was found to depend on geology and lake storage, and has been used as an index of catchment response to estimate low flow statistics at ungauged sites in a direct manner (Institute of Hydrology 1980), or indirectly by deriving regional relationships with soil type (Gustard *et al.* 1992).

Results

Synchronous Discharge Measurements

The estimated discharges in the main channel (sites 1-14, Fig. 6) are shown in Fig. 5. For comparison between campaigns the discharge was expressed in per cent of the discharge at site 1. The discharges at site 1 were 360.7 l/s, 364.2 l/s, and 430.0 l/s in 1976, 1990, and 1993, respectively. The figure shows the percentage discharges were not the same in the three years, even though the discharges at site 1 were very similar. This could be due to different flow distributions in the catchment, or to measurement errors.

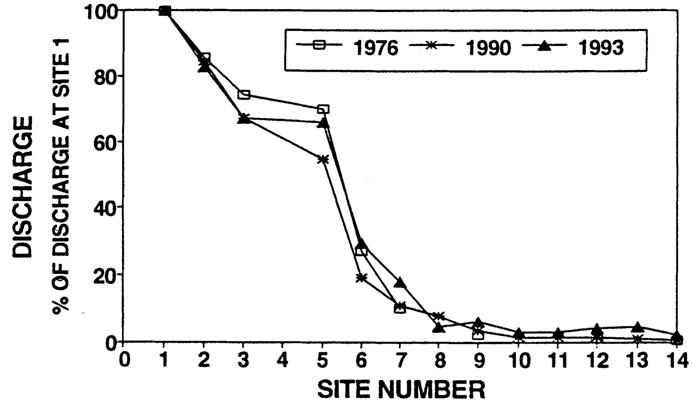

Fig. 5. Estimated discharges in per cent of the discharge at site 1 at sites in the main channel for three campaigns. For the location see Fig. 6.

The uncertainty of a discharge measurement (defined on a 95% confidence level) can be estimated by using the simplified error equation (Herschy 1978; ISO 5168, 1978). The most significant factor in this is the uncertainty, X_m, due to the limited number of verticals. This was estimated to be less than 5% for cross sections with at least 20 verticals by Herschy and ISO 748 (1979). For a decreasing number of verticals the value of X_m increases, *e.g.* for 5 verticals the X_m is estimated as 20% by Herschy and 15% by ISO 748. The ISO 748 recommends using at least 20 verticals, in which case the total uncertainty is less than ±7% if all other recommendations are followed.

The examples given by Herschy and ISO 748 are for relatively big rivers with discharges of, for example, 50 m^3/s. For smaller streams with a higher depth/width ratio, as in this study, it is more appropriate to reduce the number of verticals and increase the number of points in each vertical. Because of the different types of rivers it was decided not to use the large values of X_m given by ISO 748 (section E.3.4), which itself points out that these are guidelines that should be verified by the user.

In this study the total uncertainty of a discharge measurement was estimated to be ±6-7% at a 95% confidence level. This was based on the following results: the numerical difference between two simultaneous measurements using different instruments and cross sections, but the same velocity interpolation routine, was on average (n=5) about 2% and always less than 4%; the numerical difference between two results using programs with different routines to interpolate the velocities was on average (n=10) 1% and always less than 3%; the systematic error was insignificant because the instruments were calibrated.

An uncertainty of ±6% is greater than the difference in river flows between years shown in Fig. 5 for sites downstream site 6. As an example the discharges at site 5 were estimated as 70.0% in 1976 and 55.0% in 1990. If the measurements at site 1

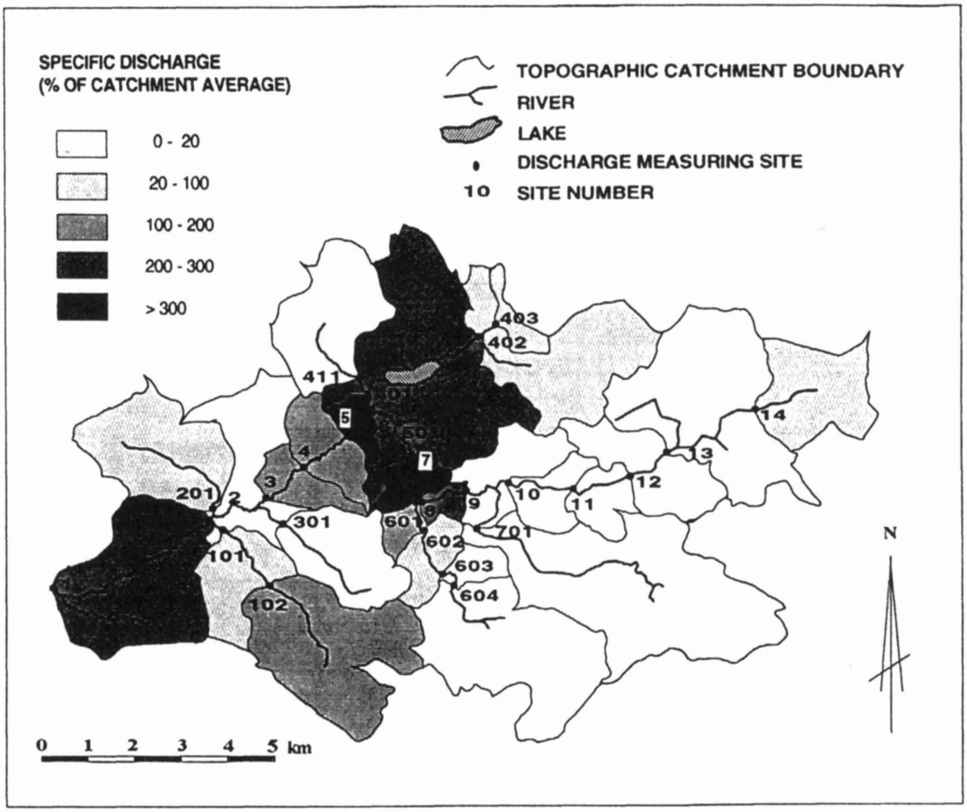

Fig. 6. Specific discharge in subcatchments found as the mean from three campaign measurements. The values are percentages of the catchment average specific discharge, which is the flow at site 1 divided by the total catchment area.

were 6% defective (negative error in 1976 and positive in 1990) as well as the measurements at site 5 (positive error in 1976 and negative in 1990), the true values at site 5 would have been 62% in both years. However, for the smaller streams the differences in percentage discharge are higher than can easily be explained by the uncertainty, *e.g.* if the results at the sites 1 and 13 were 6% defective (positive error in 1990 and negative in 1993 for site 1, and opposite for site 13) the true values would have been 1.02% in 1990 and 4.08% in 1993 compared to the Fig. 5 values 0.90% and 4.61% respectively for 1990 and 1993. Thus, the differences for the smaller streams are almost certainly due to different flow distributions within the catchment.

Fig. 6 shows the specific discharge in per cent of catchment average in each subcatchment found as the mean of the three values in Fig. 5. The simple method of using the mean of the percentages of the flow at site 1 was used because of the limited number of measurements at each site (three, but for some sites only one or two).

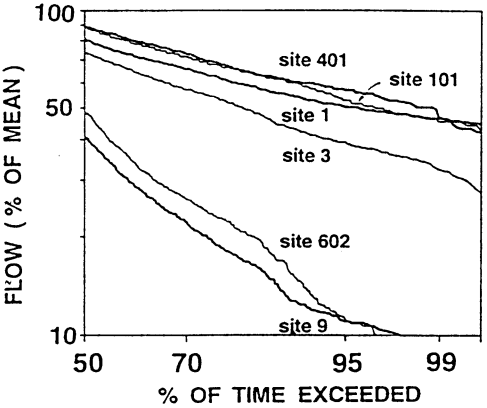

Fig. 7.
Flow duration curves for six stations for the period 1986-1989. Only exceedances higher than 50% are shown.

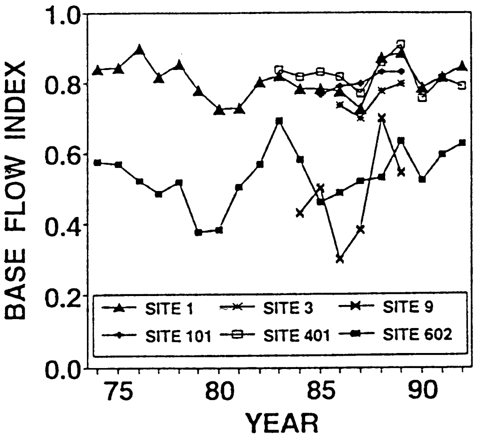

Fig. 8.
Annual baseflow indices for six gauging stations while in operation.

If more measurements were available it would be possible to derive (non-linear) relationships between the concurrent flows, or logarithmic transformations of these, at the gauged (*e.g.* site 1) and the ungauged sites (*e.g.* Riggs 1972, 1985; Clausen and Rasmussen 1993). These relationships could then be used to transfer low flow statistics at the gauged site to the ungauged sites.

Gauged Flow Records

From both the flow duration curves (Fig. 7) and the annual BFI values (Fig. 8) the stations can be grouped into two classes: the stations at sites 9 and 602 with relatively low 'low flows' coinciding with BFI lower than 0.7, and the others with relatively high 'low flows' and BFI higher than 0.7. The station at site 3 has lower exceedance flows and BFI than the other three stations in the same class.

The standard deviation of the annual BFI values ranged from 0.03 to 0.08 for records with at least four years of data, except for site 9 which had a standard deviation of 0.14. This agrees with results found by others: The Institute of Hydrology

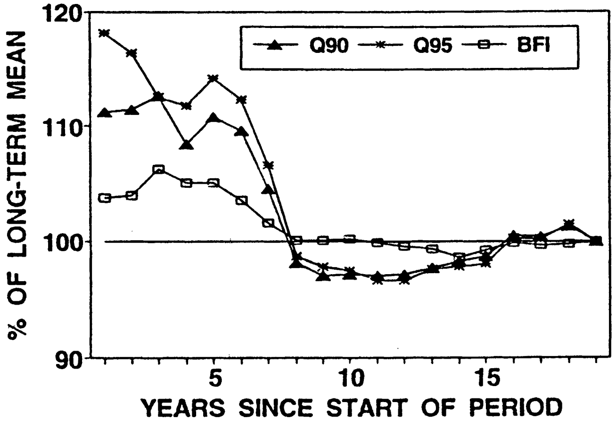

Fig. 9. The 90% (Q90) and the 95% (Q95) exceedance flows, and the baseflow index (BFI), at site 1 for cumulative periods starting 1 January 1974. Values are in per cent of the long-term mean.

(1980) and Gustard *et al.* (1992) reported standard deviations of annual BFI estimates of 0.04 and 0.05 as averages for some UK rivers, while Nathan and McMahon (1990) calculated a standard deviation of 0.14 for Australian streams.

Both the BFI, and the Q90 and Q95, were calculated for site 1 for cumulative periods from 1 January 1974 (Fig. 9). The figure shows that the BFI always deviates less from the long-term mean than the exceedance flows do. In this example it took six years for the parameters to stabilize. The calculations were repeated using other starting years, and also in these cases the BFI was found to deviate less than the exceedance flows. This suggests that the BFI is the more useful index of catchment response, particularly when only short records are available.

Low Flows and Geology in the Gjern Catchment

Both the synchronous discharge measurements and the gauged flow records showed that there is little groundwater contribution to the rivers in the eastern and southern areas (upstream sites 9 and 603) during low flow periods. In these areas the riparian deposits are dominated by clay (Figs. 2 and 3). The deeper groundwater originating from recharge in this area is either routed out of the topographic catchment, or through the aquifers to the central catchment where the specific baseflow is very high, especially in subcatchments 5-7 (Fig. 6). The specific baseflow is also low in subcatchments 2 and 301. This distribution indicates the existence of a hydrogeological barrier consisting of Tertiary or till clay in the central area, where the boundaries of subcatchments 3, 4, 6, 7, 301 and 601 meet. The baseflow is high in subcatchment 1, which is dominated by very sandy deposits. The relatively high 'low flows' at site 401 might be due to baseflow support from lake storage, but can also be explained by good contact with the thick Quaternary sand aquifer in that area.

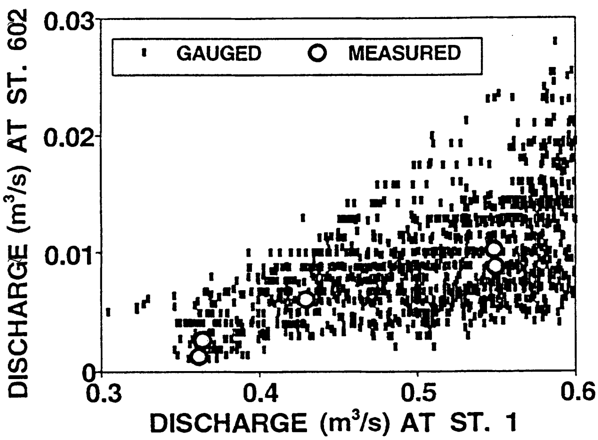

Fig. 10. Comparison between daily discharges found from stage recordings and discharge measurements using propellers at the two gauging stations at sites 1 and 602 from 1974 to 1992 (only flows lower than 0.6 m^3/s at site 1 are shown). The three lowest measured points are the campaign measurements, while the two others are calibration measurements carried out at the two sites on the same day.

Discussion

The methods used for identifying low flow regimes differ greatly. The synchronous discharge measurements are carried out at many sites in the same river network on one campaign day, and is thus very labour-demanding over a short period. The gauged flow data are collected over several years, but usually demand less intensive labour.

The results of the synchronous discharge measurements can be used for mapping the specific discharge within a catchment, whereas the gauging stations usually have a lower density and thus provide relatively little spatial information. When using synchronous discharge measurements for mapping specific discharge it is important to bear in mind the uncertainty of a discharge measurement, which necessitate the spacing between two adjacent sites to be high, so that the difference in discharge is at least 10-15%. It is also recommended to repeat the measurements in another season or another year when the flow pattern is different. However, the results of this study showed that one campaign is far better than none for estimating low flows at ungauged sites, and for interpreting groundwater flow paths.

If available, gauged flow data provide a very rapid method for identifying low flow regimes. The BFI has a very simple calculation procedure, and was found to adjust more quickly to the long-term mean than did the exceedance flows. This makes it particularly suitable for short records. The limitation of the method lies not only in the availability of flow data, but also in the fact that the recorded flow is a measure of the integrated effect at the gauging station from the total catchment. The recorded values from the gauging stations could, of course, be used in the same way as the campaign measurements to calculate the specific discharge between stations. However, the recorded values used in this study have greater errors (because of additional uncertainties related to the effect of weeds on the stage-discharge relationship) than the discharge measurements (Fig. 10), depending on the time to the nearest calibration discharge measurement. Despite these limitations the BFI and the exceedance flows are based on a large number of daily values and are therefore preferable to use compared with single discharge measurements.

The applicability of the two methods depends on the locations of the gauging stations in the river network. The method of analysing flow records is optimal where, as in the Gjern catchment, there are many gauged tributaries. In a catchment with only one main river the analyses of gauged flow data would be less useful. Here the synchronous discharge measurement technique would be suitable because of the greater spatial information conveyed by the smaller number of measurements.

Conclusions

This study showed that the analyses based on two different data sets, synchronous discharge measurements and gauged flow records, were able to distinguish between low flow regimes and relate them to different geologies in the study catchment. The results revealed a great spatial variation in low flows within the relatively small catchment because of different lithologies of the sediments. The results highlight the benefits of using synchronous discharge measurements, both for estimating low flows at ungauged sites, and for interpreting groundwater flow paths. The importance of the lithology of sediments in the study catchment for the distribution of low flows demonstrate the limitation in using simple areal measures of geology in low flow estimation. Where gauged flow data are available they provide an efficient method for identifying low flow regimes. The BFI was found to be more useful for short records than flow duration curves, and can be estimated accurately from only a few years of data.

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