Nordic Hydrology, 29 (2), 1998, 105-128
No part may be reproduced by any process without complete reference

Investigating Catchment Hydrology and Low Flow Characteristics using GIS

Eli Skop
National Environmental Res. Inst.,
DK-4000 Roskilde, Denmark

Hugo A. Loaiciga
University of California Santa Barbara, CA-95521, U.S.A.

The most frequent use of Geographic Information Systems (GIS) in hydrology has been in input/output data handling for modeling purposes, as well as in the derivation of flow direction, flow length and slope maps from Digital Elevation Models (DEMs). In turn, these maps have been merged with other maps, such as soils, land use, and vegetation maps to obtain flow velocities, isochrones, and Hydrologic Response Units (HRUs). This study presents examples of GIS applications to 1) create a depression-less DEM from contour lines of terrain elevation 2) interpolate groundwater heads based on head measurements at geo-referenced points, 3) derive topographic catchments based on the DEM and derive groundwater contributing areas to given surface points based on interpolated head values, and 4) estimate streamflow characteristics based on topographic catchments, groundwater contributing areas, and soil maps. Our results indicate the usefulness of GIS applications in spatial hydrologic analysis, interpolation, and prediction.

Introduction

GIS (geographic information systems) can be defined as integrated hardware, software and procedures designed to support the capture, management, manipulation, analysis, modeling and display of spatially-referenced data for solving complex planning and management problems (Goodchild and Kemp 1990). In the following, the term GIS is used to express the current capabilities of software products in geographic data modeling.

There are numerous previous GIS applications to input/output data processing in conjunction with hydrologic models (see *e.g.* Shea *et al.* 1993; Ross and Tara 1993) and for visualization of input and intermediate data as well as final modeling results. GIS also comes very practical in catchment and HRUs delineation. HRU's are distributed unit areas within a catchment characterized by common land use and physiographic properties such as precipitation soils, topography, *etc.* GIS can aggregate and disaggregate the spatial resolution of data and convert geographic data from one geographic data model to another (*e.g.* grids, contour lines, polygons *etc*). For example, point or line data are converted to area or surface data by spatial interpolation. Commercial GIS incorporates a variety of spatial interpolation methods. For example Arc/Info version 7.0.4 (ESRI 1995) features the following spatial interpolation methods: inverse distance weighting, kriging, trend interpolation, and a function for creating grids of terrrain elevations from point, lines and polygons based on the ANUDEM program (Hutchinson 1988; Hutchinson 1989; Hutchinson 1991; Hutchinson 1993). Spatial data analysis functionalities of GIS (*e.g.* spatial interpolation, processing of data's spatial resolution, and data model conversion) render them a flexible tool for data input/output to hydrologic models. Hydrologic models require inputs defined over a range of spatial resolutions and GIS are efficient data processors that manipulate data resolution to fit hydrologic models.

The basis for many GIS applications in surface hydrology is Digital Elevation Models (DEMs). DEMs facilitate the analysis of topographic control on water flow and have become important tools in hydrologic modeling. Benosky and Merry (1995), Jenson (1994), Moore *et al.* (1991) and Quinn *et al.* (1991) provide examples of how catchment characteristics can be extracted automatically from a DEM. A DEM is an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in a landscape (Moore *et al.* 1991). Three different DEM schemes used to represent the ground surface in DEMs are; 1) square grid network, 2) triangular irregular network (TIN) and 3) contour based network. A detailed discussion of advantages and disadvantages of these representations for different applications is given by Moore *et al.* (1991).

An important task in surface hydrology is the delineation of catchments and subcatchments. Ridge lines can be extracted from a DEM to determine catchment boundaries. Other important tasks in surface hydrology using GIS and DEMs are the automatic extraction of river networks and flow pathway delineation. These are active areas of current research (Montgomery and Foufoula-Georgiou 1993; Fairfield and Leymarie 1991; Tarboton *et al.* 1994). Local channel network extraction methods (Peucker and Douglas 1975) and global channel network extraction methods (O'Callaghan and Mark 1984) have been used in the last two decades. In global extraction methods streams are extracted from a DEM by identifying them as pixels with accumulated drainage area above some threshold value, called a "support area" (Blöschl and Sivapalan 1995). Global extraction methods have proven better suited for hydrologic analysis, as they better represent connectivity within the channel network. Contributing areas to given locations (*e.g.* stream gauging stations) and HRUs are also easily delineated using DEMs. HRUs are delineated by overlaying of thematic maps (Flügel 1996).

The usefulness of GIS and DEMs in hydrologic surface and subsurface catchment delineation is demonstrated in this work, where topographic, soils, groundwater, and hydrographic maps are processed, merged, and analyzed to give us a better understanding of runoff formation and sources at the catchment scale. Catchment hydrologic maps so derived are then used to develop statistical relationships relating soil type to low-flow indices in the Vejle Fjord catchment of Denmark.

Study Area

The Vejle Fjord catchment, located in the eastern part of Jutland, Denmark, is our study area (see location in Fig. 1). The catchment area is 736 km^2 and the land-use is predominantly agricultural. Its soils vary from coarse sands to loams. The geology is charactherized by many alternating layers. In general, however, layers from the tertiary constitute the primary aquifer in our study area. In the western part of the catchment, sandy quaternary layers overlie tertiary sand, while quaternary clayey layers overlie tertiary clay in the catchment's eastern region. In the region comprised between the eastern and western areas, quaternary clayey layers overlie tertiary sand layers. Confined aquifers predominate in the eastern part of the study area while phreatic aquifers predominate in the western part of the area. Aquifers are less contigous in the east where also the abstraction is more troublesome. Three landscape

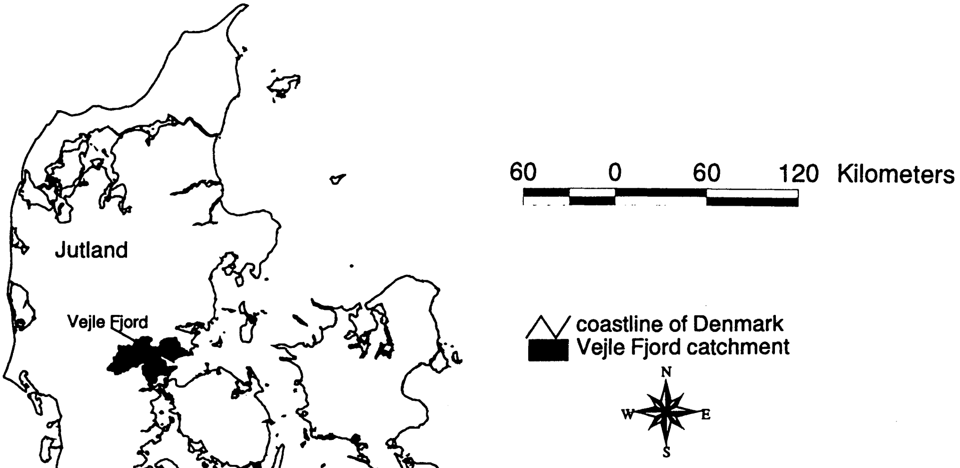


Fig. 1. Location of Vejle Fjord catchment in Denmark.

Table 1 – Main characteristics of the Vejle Fjord (Denmark) catchment and sub-catchments

	Gauging station National Environmental Research Institute ID #	290008	320001	320002	320004	320022	330004	Gauged catchments in total	ungauged catchments in total	Vejle Fjord, catchment total
	Name of stream/ catchment	Rohden River	Vejle River	Vejle River	Grejs River	Højen River	Spang River			
	location of gauging station	N.S. Årup mølle dambrug	Haraldskær	Refsgårslund	Grejsdalens planteskole	Nederbro	Bredstrup			
	topographic catchment area, km^2 1)	96.5	197.6 (64.5)	133.1	66.0	30.7	65.0	455.8	280.6	736.4
soil types, topsoil 3)	loams, %	77	37	13	58	53	84	43	28	36
	sands, %	23	59	86	42	37	9	55	58	56
	Other, %	0	4	2	0	10	7	2	17	9
soil types, subsoil 4)	loams, %	69	48	30	72	61	82	52	75	63
	sands, %	27	31	43	17	27	9	31	16	24
	Other, %	4	21	27	11	12	9	17	9	13
	Mean streamflow $l\,s^{-1}\,km^{-2}$ 5)	12.1	18.7	20.8	19.3	15.2	10.1	17.6		
	Groundwater catchment area km^2 2)	104.8	241.9 (87.3)	154.6	63.8	21.3	44.8	476.6	442.0	918.6

1) Numbers in parentheses refer to the topographic catchment area of the gauging station minus topographic catchment area of gauged sub-catchments located upstream.

2) Numbers in parentheses refer to the groundwater catchment area of the gauging station minus groundwater catchment area of gauged sub-catchments located upstream.

3) Source: Holst and Madsen 1986; Madsen *et al.* 1992.

4) Source: Petersen and Nielsen 1984; Fredericia, *et al.* 1992; Sørensen and Nielsen 1978.

5) Source: Vejle County 1995.

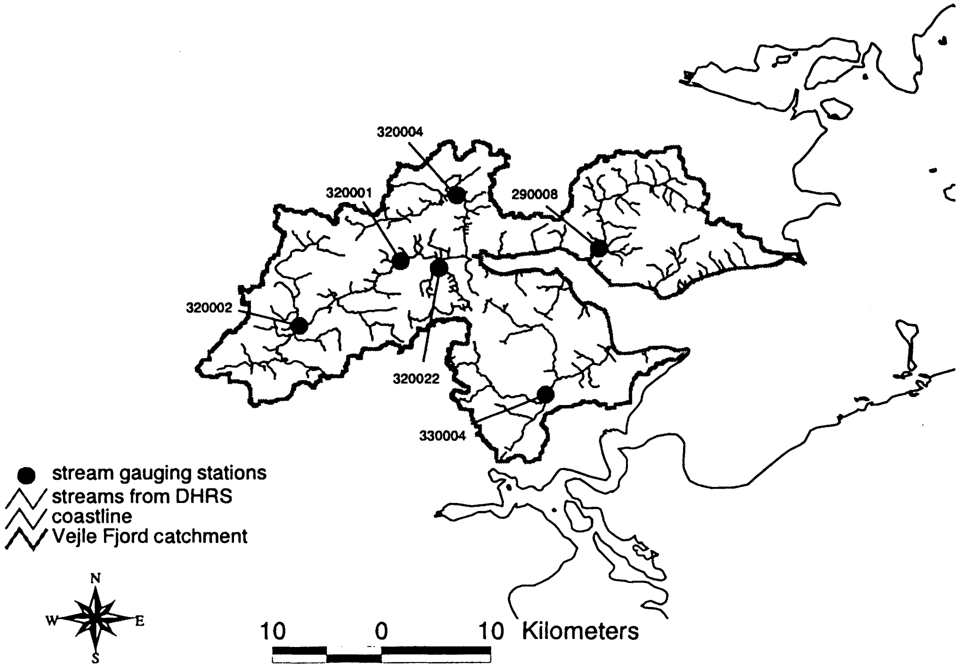


Fig. 2. Stream network from the Danish Hydrological Reference System and location of gauging stations within Vejle Fjord catchment

elements predominate in the catchment. Its eastern part is mainly younger moraine from the Weichselian glaciation period, while its western area is a mix of outwash plains from the Weichselian glaciation period and old morainic deposits from the Saalian glaciation period. Loamy soils predominate in the east (young moraine geology) and sandy soils overlie the western parts of the catchment (underlain by old moraine and outwash plains). Table 1 shows the distribution of soil types and streamflow within sub-catchments (see Fig. 2). The mean annual precipitation is 871 mm varying from about 700 mm in the eastern parts of the catchment to about 1,100 mm in its western region. The mean annual potential evapotranspiration is 554 mm and the mean monthly temperature varies from -0.2 °C in February to 15.5 °C in July. In the western part of the catchment most of the streamflow comes from groundwater, whereas in its eastern parts tile drainage constitutes a significant fraction of streamflow (especially in the winter, Simmelsgaard 1994). Maximum ground elevation is 126 m above sea level, and the groundwater heads in the primary aquifer varies between 0 m and 107 m above sea level rising up to a few m above ground at some points (confined aquifers) and reaching depths of app. 100 m below terrain at others. The location of stream gauging stations within the catchment is shown in Fig. 2.

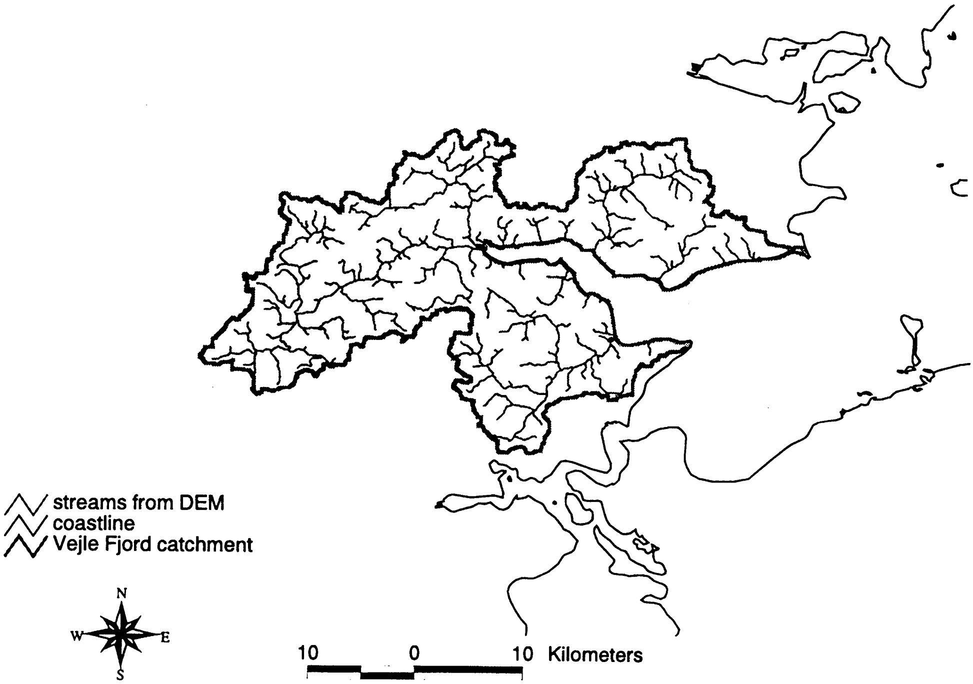


Fig. 3. Stream network derived from a digital elevation model using a single flow-direction algorithm.

Analysis of Digital Elevation Data

A number of spatial interpolation methods for converting points and contour lines to a grid have been proposed (*e.g.*, kriging, spline, distance weighting). An excellent review is given by Lam (1983). In this study the Arc/Info function named TOPOGRID based on an iterative finite difference interpolation technique (ANUDEM) was used to create a grid of terrain elevations from topographic contour lines, stream network and coast line terrain elevations. Terrain elevation at the coastline was assumed to be 0 m. Digitized topographic contour lines with a 5 m interval were read into Arc/Info together with a digitized map of the coastline at scale 1:25,000 and a digitized map of the river network in the study areas based on the Danish Hydrological Reference System (DHRS, Jensen 1992). The DHRS is based on topographic maps at a 1:25,000 scale. The chosen pixel size was 50 X 50 m.

After applying ANUDEM, closed catchments (*i.e.* inland catchments without natural overland drainage to the sea) were "filled" by raising the terrain elevation until natural drainage takes place. Closed catchments or sinks are generally rare in natural landscapes (Goodchild and Mark 1987; Mark 1988), and are herein consid-

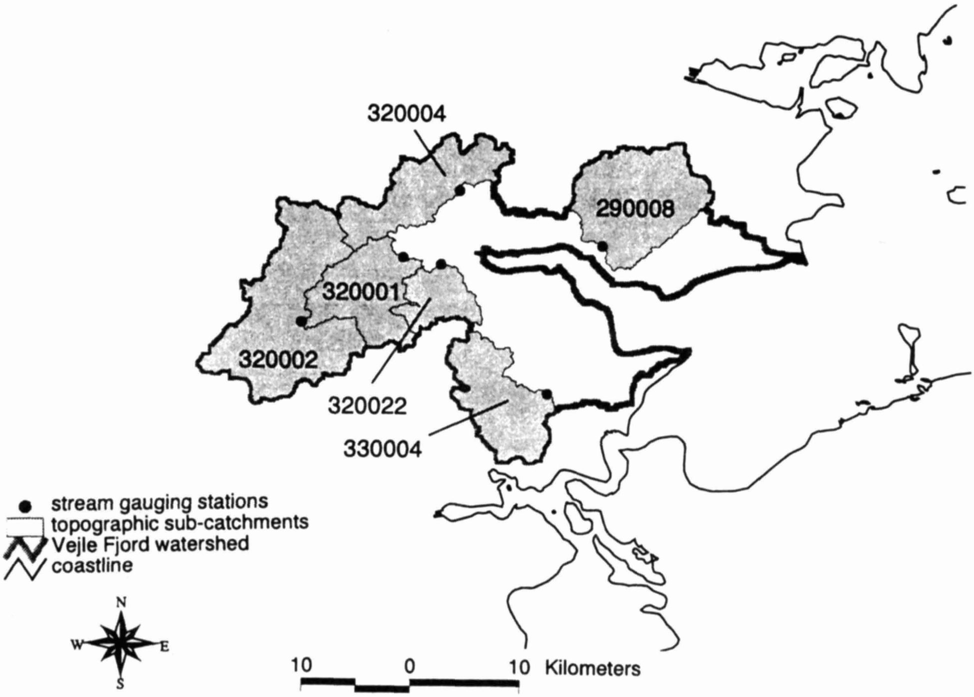


Fig. 4. Topographic boundaries of stream gauged catchments in the Vejle Fjord catchment, delineated by a single flow direction algorithm.

ered as data errors. Therefore sinks were filled to ensure proper delineation of basins and streams. A comparison between 1) the locations where water accumulates according to the Arc/Info single flow direction algorithm (which chooses as the flow-direction the direction of steepest slope among eight possible flow directions) and 2) the location of stream networks shows a similar regional pattern but some local discrepancies (compare Fig. 2 and Fig. 3). In order to ensure that the locations of DEM-derived streams correspond to that of the Danish hydrological reference system, streams can be "imprinted" or "burned" in to the DEM by artificially lowering the terrain elevation of the stream cells from the Danish hydrological reference system (Maidment 1995). In some cases, however, this technique has the disadvantage that spurious parallel streams will appear and catchment boundaries will be distorted. In this study, the river network derived from the DEM is used instead of that from the from Danish hydrological reference system in view of their overall correspondence. The river network was delineated from a depression-less DEM (*i.e.* filled and therefore without sinks) using a critical support area of 400 pixels, which corresponds to 1 km^2. The delineation of stream-gauged catchments was complicated by discrepancies between the location of stream gauging stations and the river network derived from the depression-less DEM. In three cases the stream gauging stations were found to be located in pixels adjacent to the river network. In these three cases location of stream gauging station was corrected into the river network. The topographic catchments draining to stream gauging stations were delineated, after correcting the stations' locations, by using a singe-flow direction algorithm with eight possible flow directions based on the direction of steepest slope. The algorithm delineates catchments by analysing the flow direction grid and identifying ridge lines. In a similar manner the Vejle fjord catchment was delineated as the catchment area draining to the coastline of Vejle Fjord. Fig. 4 depicts catchment topographic boundaries delineated as described above.

Analysis of Groundwater Head Data

Geo-referenced groundwater head data from more than 10,000 geological bore-hole samples collected since 1960 (Gravesen and Fredericia 1984) were read into Arc/Info together with a digitized map of the coastline. The most recent measurement was used in cases where more than one head measurement existed for the same location. Terrain elevation at the coastline was assumed to be 0 m. The chosen pixel size was 50 × 50 m. An inverse distance weighting procedure (Bussiéres and Hogg 1989; Philip and Watson 1982; Watson and Philip 1985) was applied to interpolate groundwater heads between the borings. All borings within a radius of 1 km from the interpolated points were used. In cases where less than 5 borings were found within 1 km, the search radius was increased until 5 borings were found. The weight assigned to the borings was chosen as one divided by the squared distance to the interpolated points.

After applying the interpolation procedure, depth and area of remaining sinks in the groundwater head surface were compared with pumping rates and recharge rates in order to clarify whether sinks were real phenomena or errors. The comparison did not reveal any coincidences between larger sinks and locations with high pumping rates. Sinks were therefore filled to create a depression-less groundwater head surface. In addition to surface water contributions to streamflow at the gauging stations, groundwater also contributes as baseflow. Therefore, topographic catchments to a river at a given site were delineated along with the groundwater contributing areas to the same sites. A groundwater contributing area to a given river point is the area from which groundwater have originated as groundwater but has leaked to the surface and moved as surface water to the given point.

The delineation of groundwater contributing areas to given surface points was not as straightforward a task as the delineation of topographic catchments due to the groundwater flow pattern. Groundwater flow is controlled by hydraulic conductivities and gradients. The groundwater flow-direction can, in principle, be predicted from a map of groundwater heads. One complication is, however, that groundwater discharge to riparian areas, where groundwater head exceeds terrain elevation and where the sediments between the stream and the aquifer are relatively permeable. In this case, groundwater becomes surface water, and flows according to the topography rather than according to hydraulic gradients in the subsurface. Therefore, in pixels located in areas where the topographic catchment boundaries do not coincide with the groundwater catchment boundaries, and in which the hydraulic head exceeds the ground elevation, groundwater originating in a catchment may be transferred (as cross-flow) to an adjacent catchment. The accurate prediction of groundwater flow is further complicated by difficulties in calculating the amount of groundwater that discharges to the surface in each pixel where groundwater head exceeds ground elevation. In theory this can be determined from knowledge of hydraulic gradients and conductivities. In practice, however, this requires a measurement campaign which is beyond the scope of this study.

Alternative approaches for groundwater catchment delineation have been implemented in this work. First, the total groundwater catchment to Vejle Fjord is delineated from the groundwater head map solely. The assumption made here is that groundwater follows hydraulic head gradients and emerges at the ground surface somewhere within the topographic catchment or discharges directly to the fjord bypassing the river network. Second, groundwater catchments draining to stream gauging stations have been delineated using two different methodologies. In the first method, (method 1) groundwater is routed from pixel to pixel following the steepest gradient in hydraulic head until it reaches a pixel where head elevation exceeds ground elevation. Thereafter, the water follows the topographical flow pattern. The groundwater pathway thereby ends at the point of exfiltration. In the second method, groundwater catchments draining to stream gauging stations were delineated as the areas where groundwater contributes to the entire river network within the topographic catchments. Groundwater is hence routed from pixel to pixel following the steepest gradient in head elevation, until it reaches a pixel where a stream is located, from where it follows the topographical flow pattern.

A comparison of Vejle Fjord groundwater and topographic catchments is shown in Fig. 5 and Table 1. The groundwater catchment is approximately 25% larger than the topographic catchment. Discrepancies between the surface and sub-surface water divides are largest in the north western parts, where groundwater flows towards the eastern coast of Jutland and surface water flows towards the western coast of Jutland. A comparison of groundwater catchments draining to stream gauging stations delineated by methods 1 and 2 is shown in Fig. 6 and Table 2. Discrepancies between groundwater catchments delineated using methods 1 and 2 occur in sub-catchments Nos. 320002, 320004, and 330004, where method 2 yields smaller catchments than method 1 and in sub-catchment 320022, where method 1 yields smaller catchments than method 2. Discrepancies in sub-catchment Nos. 320002, 320004 and 330004 are caused by streams where groundwater head elevation does not exceed terrain elevation. Discrepancies in sub-catchment No. 320022 are caused by areas with no streams where groundwater head elevation exceeds terrain elevation.

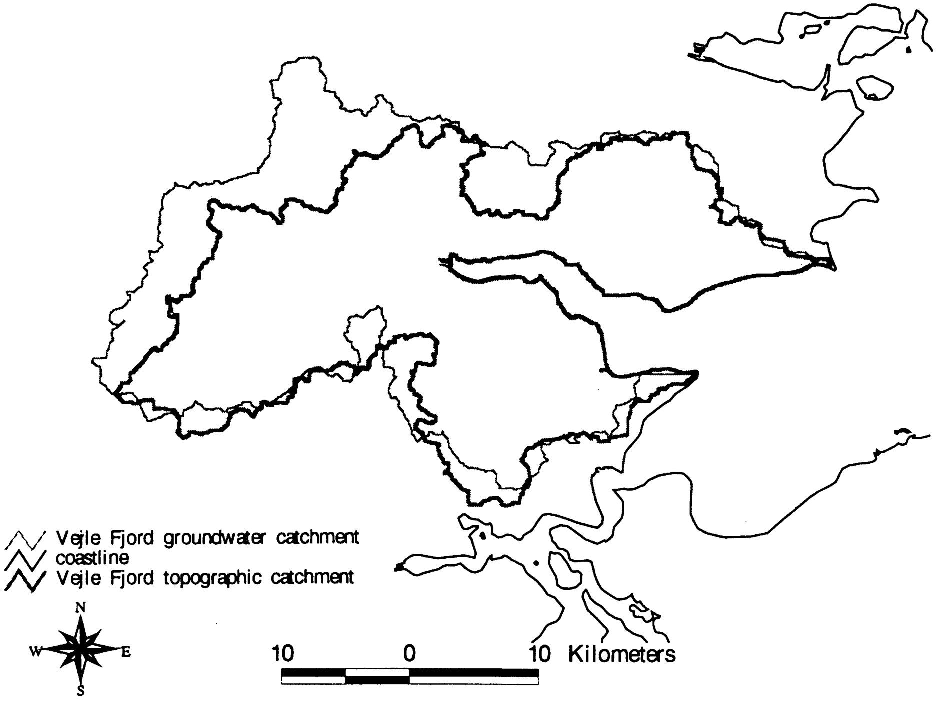


Fig. 5. Comparison Vejle Fjord groundwater catchment and topographic catchment.

Table 2 – Comparison of groundwater catchments draining to stream gauging stations delineated by two different methods

Gauging station ID #	Groundwater catchment area (method 1) km^2	Groundwater catchment area (method 2) km^2
290008	104.9	104.8
320001	83.1	87.3
320002	182.7	154.6
320004	129.7	63.8
320022	8.2	21.3
330004	59.9	44.8

Method 1 : Groundwater is routed from pixel to pixel following the steepest gradient in head elevation, until it reaches a pixel where head elevation exceeds ground elevation, from where it follows the topographical flow pattern.

Method 2: Groundwater is routed from pixel to pixel following the steepest gradient in head elevation, until it reaches a pixel where a stream is located, from where it follows the topographical flow pattern.

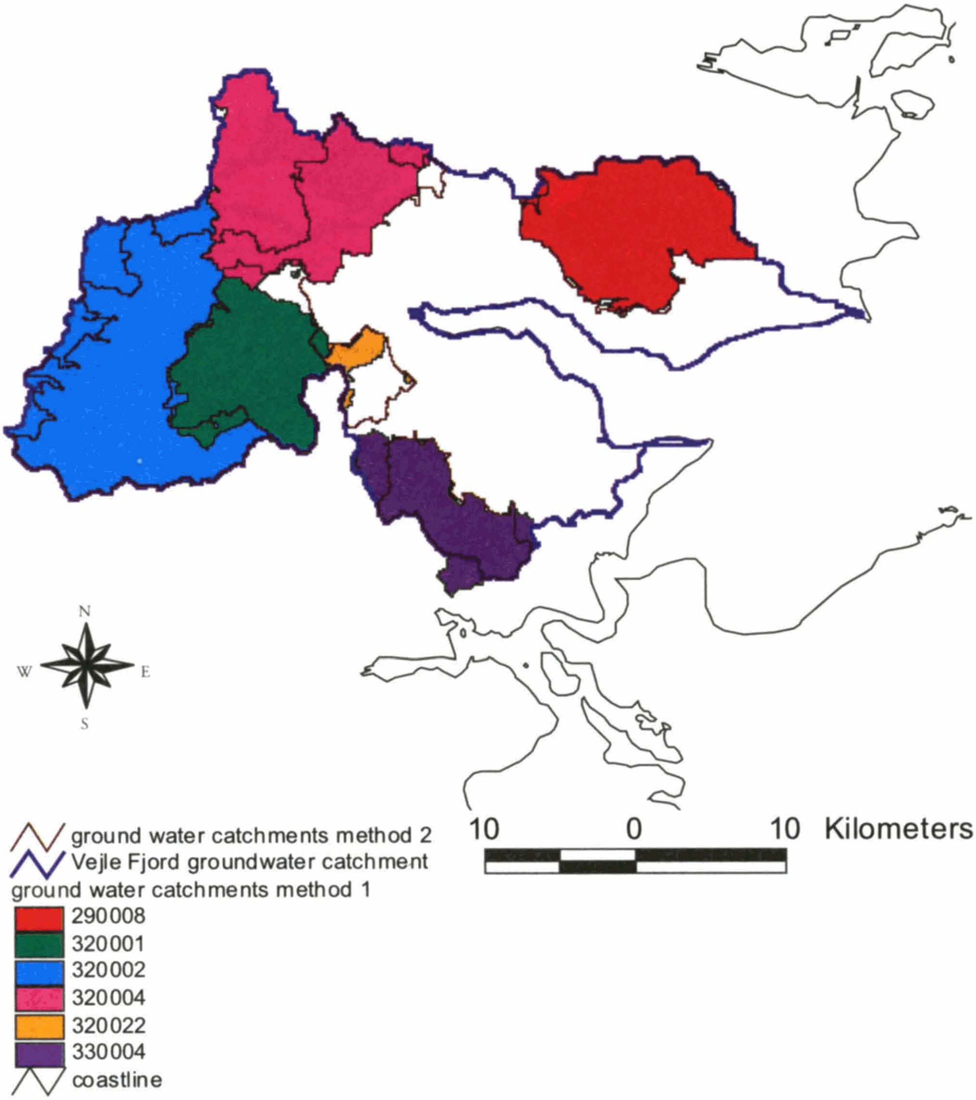


Fig. 6. Comparison of groundwater catchments draining to stream gauging stations delineated by two different methodologies. Method 1 : Groundwater is routed from pixel to pixel following the steepest gradient in groundwater head, until it reaches a pixel where head elevation exceeds ground elevation, from where it follows the topographical flow pattern.

Method 2: Groundwater is routed from pixel to pixel following the steepest gradient in groundwater head, until it reaches a pixel where a stream is located, from where it follows the topographical flow pattern.

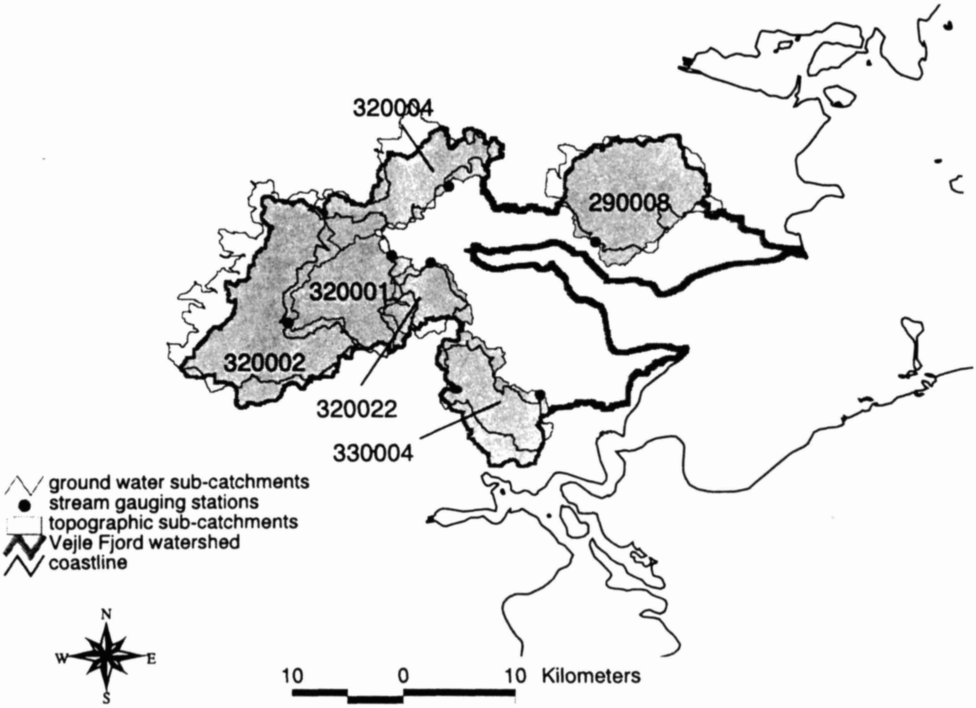


Fig. 7. Comparison of groundwater sub-catchments (method 2) and topographical sub-catchments within the Vejle Fjord catchment.

Fig. 7 shows groundwater sub-catchments delineated by method 2 and topographical sub-catchments within the Vejle Fjord watershed. For sub-catchments Nos. 320001 and 320002 the groundwater catchment area is significantly larger than the topographic catchment area, indicating that streamflow in those sub-catchments is due part to groundwater flow (baseflow) originating in neighbouring areas.

Estimating Streamflow Characteristics in Ungauged Catchments Using Soil Maps

Two low-flow statistics were correlated with two catchment characteristics to explore possible statistical correlations among them. The low flow statistics were 1) the median of annual 1-day minimum stream discharge (Nielsen 1980) divided by the mean annual streamflow, and 2) the British baseflow index (Institute of Hydrology 1980; Gustard *et al.* 1992). The median of annual minimum discharges is defined as the median value of the minimum daily discharge during each year (Nielsen 1980). The median value is the 50% quantile of the distribution function of annual minimum daily discharge. The baseflow index (BFI) (Gustard *et al.* 1992) gives the ratio of the volume under a separated hydrograph (*i.e.* baseflow only) to the volume under a total hydrograph. Baseflow separation is achieved by smoothing and separation of the daily mean flow hydrograph into direct runoff and baseflow. The separation algorithm calculates the minima of five-day non-overlapping, consecutive, periods, and, subsequently searches for turning points, which are then connected to obtain the baseflow (Institute of Hydrology 1980; Gustard *et al.* 1992). The algorithm does not attempt to simulate the groundwater flow, but rather to provide a simple method to calculate an index related to baseflow (Clausen 1995). Fig. 8 shows the hydrographs of two selected gauging stations for the period 1991-1994. The hydrographs are separated into its components and different flow patterns can be observed among the hydrographs. At station 320002 baseflow predominates the hydrograph whereas baseflow at station 330004 takes a smaller share of the area under the hydrograph.

A linear regression model was formulated for the statistical analysis

$$q_i = \alpha + \beta x_i + \epsilon_i \qquad (1)$$

Where i denotes the i^{th} catchment

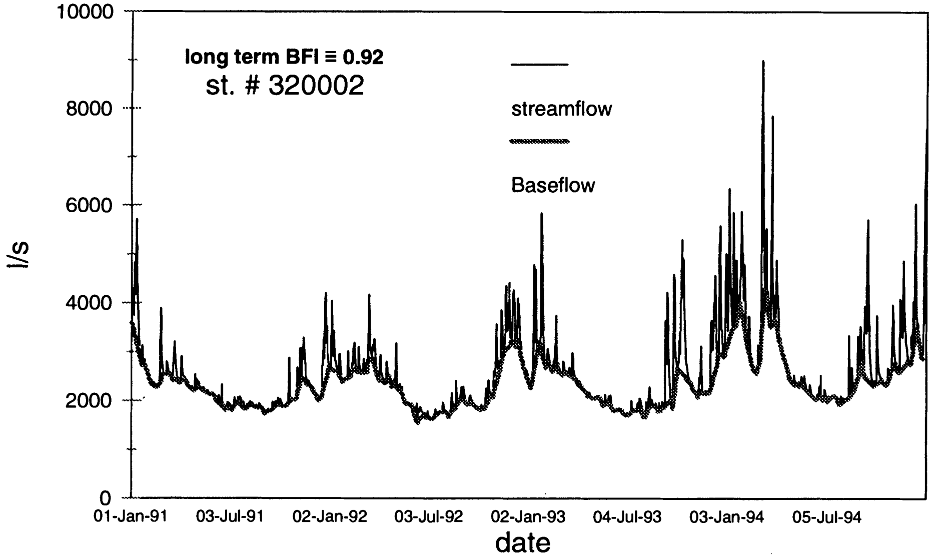
q – low-flow characteristic, either 1) median minimum/mean annual streamflow) or 2) BFI

α and β – unknown coefficients to be estimated

x_i – area of sandy soils in i^{th} groundwater catchment divided by the area of sandy soils in i'th groundwater catchment plus the area of loamy soils in i^{th} topographic catchment

ϵ_i – residual assumed to be independent and $N(0,\sigma^2)$.

The determination of the predictor variable, x, is non-trivial because the definition of catchment areas and boundaries is somewhat complex, as was discussed above. Streamflow consists of water from the topographic catchment as well as from the groundwater catchment. In the study area these boundaries do not generally coincide (see Fig. 6). Since the partitioning of net precipitation into deep percolation and horizontal surface or near surface flow path is determined by soil permeability among other things, the predictor variable x in Eq. (1) was chosen to be defined as the area of sandy soils in groundwater catchment divided by the area of sandy soils in the groundwater catchment plus the area of loamy soils in topographic catchment. The rationale behind the choice of predictor variable x is that flow is determined largely by the relative predominance of each of the two soil types, which have different permeabilities, and, thus, the regression model attempts to incorporate this feature. The model implication is that the main contributing areas to streamflow are those formed by loamy soils in topographic catchments (contributing mainly through tile-drainage) and those with sandy soils (high permeability) in the groundwater catch-



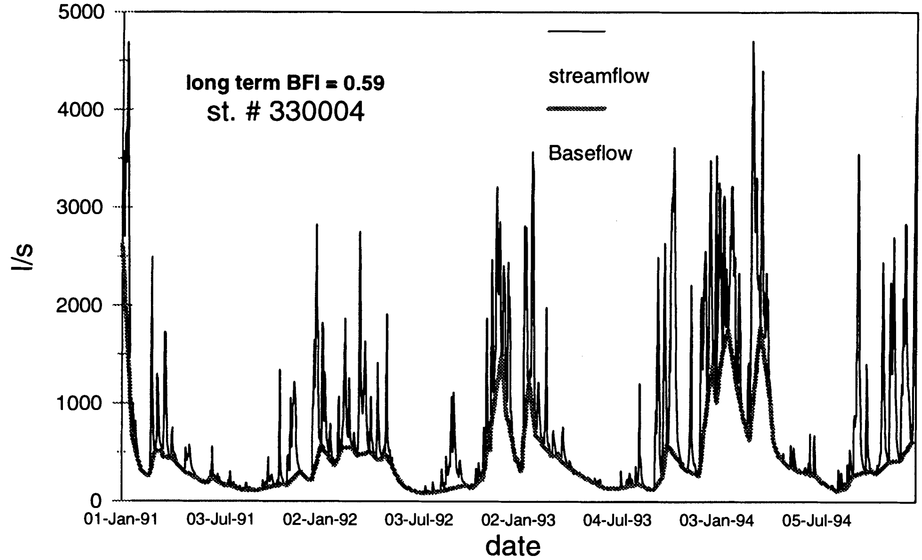


Fig. 8. Hydrographs of gauging station No. 320002 and No. 330004 for the period 1991-1994 separated into their components.

ment (contributing mainly through deeper groundwater). The larger the area of sandy soils in the groundwater catchment, the larger the baseflow contribution to streamflow. Normalization of the sandy soil area in the groundwater catchment by the sum of sandy and loamy soil areas in the groundwater and topographic catchments, respectively, takes account of the fact that part of the streamflow derives from surface runoff and tile drainage over loamy soils. The calculation of sandy and loamy soil areas within catchments was based on two digitized soil maps: one for the topsoil and one for the subsoil. These maps were read into the GIS and overlaid by maps of topographic catchments and groundwater catchments derived from the depression-less DEM and groundwater head map as described in a previous section. The groundwater catchments used here are delineated as the groundwater catchments contributing to the entire river network within the topographic catchments (method 2 explained above).

The topsoil map is based on a nation-wide mapping of Danish soils carried out in the 1970s (Holst and Madsen 1986; Madsen *et al.* 1992). This soil map is based on 35,000 samples taken in the plough layer and 500 samples taken in the 35-55 cm soil layer in agricultural areas. This corresponds to approximately one sample per km^2 of Danish agricultural area. The subsoil map was digitized from the geological mapping of the Quarternary of Denmark, at scale 1:25,000 (Petersen and Nielsen 1984; Fredericia *et al.* 1992; Sørensen and Nielsen 1978).

Table 3 shows BFI, median minimum/mean annual streamflow and the values of the predictor variables x as defined above for each of the gauging stations. Fig. 9 shows plots of median minima/mean annual streamflow and the BFI against the predictor variable x as defined above for both top soil and subsoil conditions. Both soil maps correlate relatively well with streamflow characteristics. A summary of regression analysis statistics is presented in Table 4, which show r^2 values between 0.77 and 0.84 using the subsoil map, and 0.80 and 0.90 using the topsoil map. Median minimum divided by the mean annual streamflow shows a better correlation with either predictor variable than the BFI.

Table 3 – BFI, Median minimum / mean annual streamflow, and predictor variable x for gauging stations in Vejle Fjord Catchment

Gauging station ID #	BFI	Median minimum/ mean annual streamflow	predictor variable x (topsoil)	predictor variable x (subsoil)
290008	0.70	0.28	0.26	0.31
320001	0.73	0.48	0.70	0.45
320002	0.92	0.72	0.90	0.66
320004	0.73	0.40	0.36	0.14
320022	0.70	0.30	0.42	0.24
330004	0.59	0.19	0.04	0.06

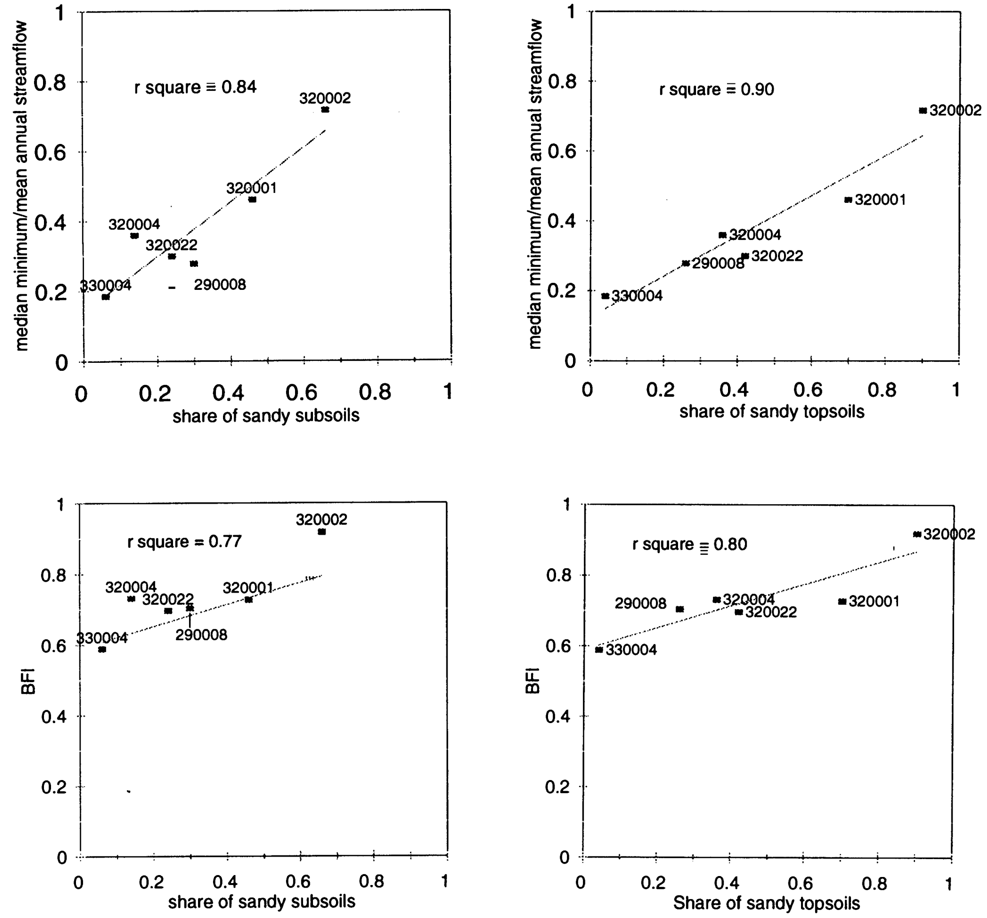


Fig. 9. Plot of low flow measures against area with sandy topsoils in percent of total area in catchment.

Discussion

The methods presented in this article involve choosing among a number of competing alternatives for selecting spatial interpolation method, pixel size, flow direction algorithm, river derivation technique and critical support area. Each of these are fields of current research, for which an in depth analysis is beyond the scope of this study. It has been demonstrated how different data and data analysis techniques can be merged to provide simple tools for estimating low-flow characteristics. The following discussion highlights key issues pertinent to our choice of hydrologic data analysis within a GIS framework.

Table 4 – Linear regression analysis of low flow characteristics and soil types

Dependent variable (predicted) q	independent variable (predictor) x	r^2	coefficient β	coefficient α	Standard error of q estimate
Median minimum/ mean annual streamflow	area with sandy **topsoil**	0.90	0.577	0.126	0.06
BFI	area with sandy **topsoil**	0.80	0.310	0.590	0.05
Median minimum/ mean annual streamflow	area with sandy **subsoil**	0.84	0.783	0.140	0.08
BFI	area with sandy **subsoil**	0.77	0.429	0.596	0.06

Spatial Interpolation

There is a broad variety of well-known spatial interpolation methods. One commonly used method is kriging, which in several cases has shown greater accuracy compared to other interpolation methods (Rouhani 1986; Weber and Englund 1992). However, in some instances, other interpolators have outperformed kriging (Philips *et al.* 1992; Lasslet *et al.* 1987). Pavlik *et al.* (1996) evaluated kriging and inverse distance weighting interpolation in a computational experiment. Their results indicate that the choice of optimal interpolator may depend on the data characteristics. The inverse distance weighting method, for instance, is not suitable for clustered data. Wilmott and Robeson (1995) compared two traditional interpolators, inverse distance weighting and Renka's (1984) triangular decomposition method with climatologically aided interpolation for interpolation of terrestrial air temperature. Wilmott and Robeson (1995) found that climatologically aided interpolation resulted in lower interpolation errors. The ANUDEM iterative finite difference interpolation technique was chosen to interpolate terrain elevation data in this article. ANUDEM was developed specifically for hydrological purposes. A disadvantage of using contour lines for data interpolation, as ANUDEM does, is the over-representation of points along the contour lines and the under-representation of points between the lines. In flat areas, (for example as in the river valley of Vejle) fewer contour lines can be represented, which creates difficulties in the determination of correct flow-direction and channel network location. The ANUDEM spatial interpolator, however, is designed to minimize errors that arise when contoured data are used for spatial interpolation.

The assumption made in this study, that closed catchments are data errors, may not be in agreement with terrain conditions. Depressions in landscape are a scale dependent phenomenon and they do occur. At the micro level (fine resolution *e.g.* milimetres and centimetres) many small depressions exist. However, when increasing the resolution to metres or kilometres, the frequency of occurrence of depressions and the area of those depressions decrease.

Although the hydrologic significance of depressions is not a well studied phenomenon, it is evident that it can influence the hydrologic response of a catchment. Closed catchments observed in the Vejle Fjord region are the remnants of a landscape where erosion have not yet obliterated the more recent glacial deposition. Closed catchment in the Vejle Fjord catchment are, however, often tile-drained, and water is permitted to drain to nearby streams through tile drainage.

Groundwater head was interpolated in this work by means of an inverse-distance weighting technique. Groundwater head data contain sampling errors that arise from long-term and seasonal variations that occur over extented periods of record keeping. In a few cases head measurements may belong to hydrologically disconnected formations. This further compounds groundwater head interpolations. Interpolated groundwater heads are mainly used for groundwater catchment delineation. Delineation of groundwater contributing areas to a surface point as defined above is encumbered with difficulties caused by groundwater/surface water interactions and by our lack of knowledge of these interactions. Two alternative methods are proposed herein to carry out the hydrologic analysis when such catchment cross-flow occurs.

DEM Resolution

An appropriate DEM resolution is dictated by the density of data points from which it is created. At coarse resolutions, several data points may be allocated to the same pixel leading to data averaging and surface smoothing in the fitted DEM in relation to the actual surface (Hutchinson 1996). Ideally DEM resolution should be chosen such that no more than one point is allocated to each pixel. In this fashion, DEM calculated slope will approximately match the terrain slope implied by the data points. Minor discrepancies in terrain representation, which depend on pixel size and slope, may arise from the fact that data points are assumed located at the centers of the pixels.

Quinn *et al.* (1991) compared the performance of DEMs by analyzing pixel sizes of 12.5 m and 50 m in a small catchment of 1.36 km^2. The contour interval used to derive the DEM was 1m. Quinn *et al.* (1991) found that the coarser resolution elevation map appeared to be realistic overall, although considerable details were lost. They also compared the overall dynamics of the soil moisture regime represented by the topographic index from the TOPMODEL (Beven and Kirkby 1979). Their results indicated lager topographic indices when 50 m pixels were used in the DEM.

TOPMODEL was also used in a study by Bruneau *et al.* (1995), who studied the importance of spatial and temporal resolution on hydrologic modeling results. They used data for a 12 km^2 catchment in France during two winter months. The terrain elevations in the catchment range from 65-136 m. The influence of DEM spatial resolution was analysed using six different DEMs with pixel sizes of 20, 25, 30, 50, 70, and 100 m. The DEMs were derived from scanned contour maps at 1:10,000 scale. The Bruneau *et al.* (1995) study determined that as the pixel size increases: 1) the occurrence of pit and dam features increased; 2) catchment size decreases by about 5% between the coarsest and the finest resolution; 3) the relative frequency of low-slope angles decreases; 4) the percentage of large topographic indices values increases; and 5) the change in location of the channel network is almost negligible, although the channel network branching is dependent on pixel size.

Quinn *et al.* (1995) applied TOPMODEL, with a DEM pixel size of 50 m, and claim to have achieved a good description of macro-scale flux. Variations in pixel size caused only small discrepancies in the prediction of the catchment hydrographs. On the other hand, the local flux and detailed catchment behavior could not be described satisfactorily with the 50-m pixel DEM. The 50-m DEM tends to overlook the existence of low-order streams. Quinn *et al.* (1995) established that coarse-resolution DEMs makes it difficult to accurately delineate catchment boundaries.

Wolock and Price (1994) and Zhang and Montgomery (1994) studied the effects of DEM resolution on TOPMODEL hydrologic predictions. Both studies found that predicted hydrographs were significantly affected by the DEM resolution.

The present article adopted a 50-metre DEM pixel size for terrain and groundwater head representation. Coarser resolutions introduce large errors, while a finer resolution imposes an unreasonable computational burden.

Flow Direction Algorithm and River Network Extraction

Several flow algorithms have been proposed in the literature. The early and simplest ones use a four-direction algorithm, where water flows through one of the four pixel sides following the steepest slope. The most commonly used algorithm incorporated into contemporary raster GIS (*e.g.* Arc/Info Grid module) is the eight-direction flow algorithm, in which water flows through one of the four pixel sides or through on of the four pixel corners following the steepest slope. In contrast to single flow direction algorithms, multiple flow direction algorithms assume that flow occurs in all down-slope directions from any given point. Wollock and McCabe (1995) concluded that single and multiple flow direction algorithms may produce discrepancies in the predicted spatial distribution of soil moisture content. However, simulated streamflow and streamflow partitioning are not markedly affected by the choice of computational algorithm (*i.e.* single or multiple flow direction). Quinn *et al.* (1991) concluded that a multiple flow algorithm gives a more realistic pattern of accumulated drainage area on the hillslope portion of a catchment, while the single flow algorithm is more suitable once the flow has entered the permanently incised drainage system.

The choice of support area is a contentious issue (Blöschl and Sivapalan 1995). There is an ongoing debate on how (critical) support areas are determined best, and whether or not support areas should be constant within a given region. Montgomery and Foufoula-Georgiou (1993) suggest that a slope-dependent critical support area is both theoretically and empirically more appropriate for defining the initiation of the channel network. Quinn *et al.* (1995) concluded that an optimal critical support area in a DEM of specified resolution can be defined via the digital terrain analysis from TOPMODEL (Beven and Kirkby 1979). Tarboton *et al.* (1994) suggested a support area determined as the minimum value, which produces a channel network that conforms to established scaling laws.

Our work adopted a constant critical support area of 1 km^2. Discrepancies between model derived stream network and stream network implied from topographic maps may be caused by stream regulation, which is common in the study area. DEM derived stream networks describe the natural drainage network not taking anthropogenic changes into account. Furthermore, stream appearance is strongly dependent on the groundwater system and thus the geology which is ignored, when using topographical data only. Also, any definition of stream network is scale dependent. The fact that some streams advance and retreat seasonally adds a temporal dimension to this matter. Ideally the critical support area should be variable reflecting the spatial variability in precipitation and evapotranspiration throughout the study area.

Conclusion

Topographic, soils, hydrographic, and groundwater head maps were processed, combined, and analyzed to delineate surface water and groundwater catchments. The tools applied for the analysis were a variety of GIS built in spatial analysis functions. The procedure applied consisted of: 1) creation of depressionless DEM from contour lines of terrain elevation, 2) extraction of river network from the depressionless DEM based on exceedance of threshold values of GIS-predicted flow accumulation, 3) creation of depressionless groundwater head map, 4) delineation of surface water and groundwater catchments draining to selected gauging stations, 5) overlay of soil maps with maps of catchment boundaries to calculate the fraction of subcatchments underlain by a specific soil types. The outlined procedure showed: 1) spatial discrepancies between topographic and groundwater catchment boundaries, 2) streamflow formation sources, and how these are spatially associated with varying soil types, topography, and groundwater head fields. The estimation of catchment boundaries (surface and subsurface), catchment areas, and flow fields was made possible by the application of GIS to data from the Vejle Fjord catchment in Denmark.

The spatial hydrologic data analysis leads to the formulation of a regression model for low-flow indices in gauged catchments within the study area. A strong statistical association was found between the British baseflow index and a predictor variable defined in terms of the fraction of sandy soils in the groundwater catchment, as well as between the Danish minimum flow index and the same predictor variable. Thus the utility of GIS in hydrographic characterization has been extended in this work to the development of predictive flow models for ungauged catchments.

Acknowledgements

This study has been financed by a grant from the Danish Research Academy. Permission to use the top-soil map was granted by the Danish Institute of Plant and Soil Science. Use of the sub-soil map was granted by the Geological Survey of Denmark. Software for baseflow separation was kindly provided by Bente Clausen, Aarhus University and Brian Kronvang, National Environmental Research institute. Use of contour lines of terrain elevation was authorized by the Map and Cadastral Agency of Denmark.

References:

Benosky, C. P,. and Merry, C. J. (1995) Automatic extraction of watershed characteristics using spatial analysis techniques with application to groundwater mapping, *J. Hydrol. Vol. 173*, pp. 145-163.

Beven, K. J., and Kirkby, M. J. (1979) A physically based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull. Vol. 24* (1), pp. 43-69.

Blöschl, G., and Sivapalan, M. (1995) Scale issues in hydrological modelling: A review, *Hydrological Processes, Vol. 9* pp. 251-290.

Bruneau, P., Gascuel-Odoux, C., Robin, P., Merot, Ph., and Beven, K. (1995) Sensitivity to space and time resolution of a hydrological model using digital elevation data, *Hydrological processes 10th anniversary issue*, pp. 55-67.

Bussiéres, N., and Hogg, W. (1989) The objective analysis of daily rainfall by distance weighting schemes on a mesoscale Grid, *Atmosphere-Ocean Vol. 27* (3), pp. 521-541.

Clausen, B. (1995) Discharge data collection and analysis strategies in low flow studies, *Nordic Hydrology Vol. 26*, pp. 191-204.

ESRI (1995) Arc/Info version 7.0.4. Environmental Systems Research Institute, Redlands, California.

Fairfield, J., and Leymarie, P. (1991) Drainage Networks from grid digital elevation models, *Water Resources Research, Vol. 27* (5) pp. 709-717.

Flügel, W-A. (1996) Application of GIS to derive Hydrological Response Units for hydrological modeling in the Bröl catchment, Germany. HydroGIS 96: Appliction of Geographic information systems in hydrology and water resources Management. Proceedings of the Vienna conference, Vienna, Austria April 1996.

Fredericia, J., Pedersen, S. A., and Petersen, K. S. (1992) Geological Mapping. In: Annual Report, Geological Survey of Denmark. pp. 65-68.

Goodchild, M. F., and K. K. Kemp (1990) Introduction to GIS. NCGIA core curriculum. National Center for Geographic Information and Analysis, University of California, Santa Barbara.

Goodchild, M. F., and Mark, D. M. (1987) The fractal nature of geographic phenomena, *Annals of Association of American Geographers, Vol. 77* (2) pp. 265-278.

Gravesen, P., and Fredericia, J. (1984) ZEUS-geodatabase system. Borearkivet. Danmarks Geologiske Undersøgelse, rapport serie D nr. 3.

Gustard, A., Bullock, A., and Dixon, J. M. (1992) Low flow estimations in the United Kingdom, Institute of Hydrology, Report no. 108.

Holst, K. Aa., and Madsen, H. B. (1986). The elaboration of drainage class maps for agricultural planing in Denmark, *Landscape and Urban Planning, Vol. 13* pp. 199- 218.

Hutchinson, M. F. (1988) Calculation of hydrologically sound digital elevation models. Third international symposium on spatial data handling, Sydney, Columbus, Ohio: International Geographical Union.

Hutchinson, M. F. (1989) A new procedure for gridding elevation and stream line data with automatic removal of spurious pits, *J. Hydrol., Vol. 106*, pp. 211-232.

Hutchinson, M. F., and Dowling, T. I. (1991) A continental hydrological assessment of a new grid-based digital elevation model of Australia, *Hydrological Processes, Vol. 5*, pp. 45-58.

Hutchinson, M. F. (1993) Development of a continent-wide DEM with applications to terrain and climate analysis. In: M. F. Goodchild *et al.* (eds.), *Environmental modeling with GIS*, New York, Oxford University Press, pp. 392-399

Hutchinson, M. F. (1996) A locally adaptive approach to the interpolation of digital elevation models. Preliminary proceedings of the third international conference/workshop on integrating geographic information systems and environmental modeling, Santa Fe, January 21-25 1996.

Institute of Hydrology (1980) Low flow studies, research report No.1, Institute of Hydrology, Wallingford, United Kingdom, approx 300 pp.

Jensen, J. B. (1992) Hydrologisk reference fra Miljøstyrelsen (in Danish), *Landinspektøren nr. 4*, pp. 200-205.

Jenson, S. K. (1994) Applications of hydrologic information automatically extracted from digital elevation models. In Beven, K. J. and Moore, I. D. (eds.): *Terrain analysis and distributed modelling in hydrology*, John Wiley and Sons.

Lam, N. S. (1983) Spatial interpolation methods: A review, *The American Cartogra pher, Vol. 10* (2), pp. 129-149.

Lasslet, G. M., McBratney, A. B., Pahl, P. J., and Hutchinson, M. F. (1987) Comparison of several spatial methods for predicting soil pH, *J. Soil Science, Vol. 38*, pp. 325- 341.

Madsen, H. B., Nørr, A. H., and Holst, K. A. (1992) *Atlas of Denmark. Series 1, volume 3.* The Danish Soil Classification. The Royal Danish Geographical Society, Rosendahl Press.

Maidment, D. (1995) GIS and hydrologic modeling – an assessment of progress. Preliminary proceedings of the third international conference/workshop on integrating geographic information systems and environmental modeling, Santa Fe, January 21-25 1996.

Mark, D. M. (1988) *Network models in Geomorphology. Modeling in geomorphological systems*, John Wiley.

Montgomery, D. R., and Foufoula-Georgiou, E. (1993) Channel network source representation using digital elevation models, *Water Res. Res. Vol. 29* (12), pp. 3925- 3934.

Moore, I. D., Grayson, R. B., and Ladson, A. R. (1991) Digital terrain modelling: A review of hydrological geomorphological and biological applications, *Hydrol. Processes, Vol. 5* pp. 3-30.

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.

O'Callaghan, J., and Mark, D. M. (1984) The extraction of drainage networks from digital elevation data, *Computer vision graphics and image processing, Vol. 28,* pp. 323-344.

Pavlik, C. E., Zimmerman, D., Ruggles, A. J., and Armstrong, M. (1995) The Impact of autocorrelated error on the interpolation of statistical surfaces, *GIS/LIS proceedings Nashville Tennessee*, Vol. 2, pp. 814-823.

Petersen, K. S., and Nielsen, A. V. (1984) Outline on Danish Drift Geology. The preliminary Geological maps (1:25.000) as a basis of information on Danish soils and surface conditions. Danish Geological Survey, intern report no. 27.

Peuker, T. K., and Douglas, D. H. (1975) Detection of surface-specific points by local parallel processing of discrete terrain elevation data, *Computer graphics and image processing, Vol. 4,* pp. 375-387.

Philip, G. M., and Watson, D. F. (1982) A precise method for determining contoured surfaces, *Australian petroleum exploration association journal, Vol. 22,* pp. 205-212.

Philips, D. L., Dolph, J., and Marks, D. (1992) A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain, *Agricultural and Forest Meteorology, Vol. 58,* pp. 19-141.

Quinn, P., Beven, K., Chevallier, P. ,and Planchon, O. (1991) The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models, *Hydrol. Processs., Vol. 5,* 59-79

Quinn, P., Beven, K., and Lamb, R. (1995) The ln(a/tan) index: How to calculate it and how to use it within the topmodel framework, *Hydrol. Processs., Vol. 9,* pp. 161- 182

Ross, M. A., and Tara, P. D. (1993) Integrated hydrologic modeling with geographic information systems, *J. of Water. Resour. Planning and Manangement, Vol. 119* (2), pp. 129-140.

Rouhani, S. (1986) comparative study of groundwater mapping techniques, *Groundwater Vol. 24* (2), pp. 207-216.

Seyfried, M. S., and Wilcox, B. P. (1995) Scale and the nature of spatial variability: Field examples having implications for hydrologic modeling, *Water Resources Research, Vol. 31* (1), pp. 173-184.

Shea, C., Grayman, W., Douglas, D., Males, R. M., and Sushinsky, P. (1993) Integrated GIS and hydrologic modeling for countywide drainage study, *J. of Water. Resour. Planning and Management, Vol. 119* (2), pp. 112-128.

Simmelsgaard, S. E. (1994) Nitrate nitrogen in subsurface drainage water in Denmark 1971-91, Institute of Plant and Soil Science, Ministry of Agriculture. Report no. 47. Lyngby, Denmark.

Sørensen, H., and Nielsen, V. A. (1978) The Geological mapping of Denmark. The present state of the mapping – proposals for the future mapping, Danish Geological Survey, Series A, No. 2.

Tarboton, D. G., Bras, R. L., and Rodriguez-Iturbe, I. (1994) On the extraction channel networks from digital elevation data. In Beven, K. J. and Moore, I. D. (eds.): *Terrain analysis and distributed modelling in hydrology*, John Wiley and Sons.

Vejle County (1995) Afstrømningsmålinger 1994 (in Danish) (Streamflow measurements 1994). Vejle County, Technics and Environment, Damhaven 12, 7100 Vejle, Denmark.

Watson, D. F., and Philip, G. M. (1985) A refinement of inverse distance weighting interpolation, *Geo-Processing, Vol. 2,* pp. 315-327.

Weber, D. D., and Englund, E. J. (1992) Evaluation and comparison of spatial interpolators, *Mathematical Geology, Vol. 24* (4), pp. 381-391

Wolock, D. M., and McCabe Jr., G. J. (1995) Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL, *Water Resources Research, Vol. 31* (5), pp. 1315-1324.

Wolock, D. M., and Price, C. V. (1994) Effects of digital elevation model map scale and data resolution on a topography-based watershed model, *Water Resources Research, Vol. 30* (11), pp. 3041-3052.

Zhang, W., and Montgomery D. R. (1994) Digital elevation model grid size, landscape representation, and hydrologic simulations, *Water Resources Research, Vol. 30* (4), pp. 1019-1028.

Received: 19 March, 1997
Revised: 12 September, 1997
Accepted: 28 November, 1997

Address:
Eli Skop,
National Environmental Research, Institute,
Dept. of Policy Analysis,
P. O. Box 358,
DK-4000 Roskilde,
Denmark.
E-mail: es @ dmu.dk

Hugo A. Loaiciga,
University of California Santa Barbara,
Department of Geography,
CA-95521,
U.S.A.
Email: hugo @ geog.ucsb.edm