

Estimation of saturation excess overland flow areas: comparison of topographic index calculations with field mapping

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Abstract In a mountainous river basin in southwest Germany, the applicability of the topographic index concept for the regionalization of source areas of saturation excess overland flow was tested by comparison with mapped saturated areas. Topographic index calculations based on gridded digital elevation data were performed with different parameterizations of flow pathway concentration and initiation of channels. Saturated areas were mapped according to pedological and geobotanical criteria. The index calculation method was shown to influence the spatially distributed results and a method best corresponding to mapped saturated areas was determined. The comparison of field survey with the spatial pattern of high index values reveals the importance of features other than topography for generation of saturated areas in the study area. The concept of the topographic index requires a critical review with respect to calculation algorithms and characteristics of the study area before its application as a tool for the regionalization of hydrological properties.

INTRODUCTION

The identification and modelling of different runoff components is an important aim in understanding runoff generation mechanisms and solute transport behaviour in hydrological systems. A process contributing to quick runoff components is saturation excess overland flow (Cappus, 1960; Dunne & Black, 1970). One approach in determining the location of source areas of saturation excess overland flow and their time-variable extension is based on topographic catchment analysis, as implemented in the TOPMODEL concept with its associated topographic index (Beven & Kirkby, 1979). Describing the tendency of water to accumulate and to move downslope at any point in the study area, the topographic index can be used as a tool for the regionalization of soil moisture status or saturation excess overland flow areas. On the basis of grid digital elevation models, various methods for deriving the topographic index are described in the literature (e.g. Quinn *et al.*, 1991; Holmgren, 1994; Quinn *et al.*, 1995). These methods lead to a wide range of differing spatial patterns and distribution functions. Few attempts have been made to compare the spatial

distribution of the topographic index with field observations distributed over large areas. Merot *et al.* (1995) carried out a comparison of the index with characteristics of soils indicating their water regime. Rodhe & Seibert (1996) compared the spatial pattern of the topographic index with the occurrence of mires in Swedish drainage basins. In these studies, however, only one method of index calculation was used. Here the focus is on an evaluation of different algorithms for representing the spatial distribution of mapped saturated areas in a mountainous river basin.

METHODS

The topographic index I implemented in TOPMODEL (Beven & Kirkby, 1979) is calculated as $I = \ln(a/\tan\beta)$, where a is the local upslope area per unit contour length and β is the local slope angle of the ground surface. The higher the value of the index, i.e. the larger the local upslope area and the smaller the local slope angle, the lower is the saturation deficit that can be expected in a soil profile. Areas with a saturation deficit equal to zero are saturated to the surface and are supposed to contribute to saturation excess overland flow. Locations with the same index value are assumed to show the same characteristics concerning soil moisture status. This is predominantly based on the assumptions of uniform groundwater recharge and uniform transmissivity over the study area. Consequently, the topographic index is an expression of hydrological similarity (e.g. Beven *et al.*, 1995).

The topographic index used was based on a digital elevation model with a grid size of 50 m \times 50 m. In order to determine the local upslope area of every grid cell, flow directions between cells are established and a procedure corresponding to a "routing of area" along flow pathways is required. Various methods are presented in the literature (e.g. O'Callaghan & Mark, 1984; Freeman, 1991; Quinn *et al.*, 1991; Lea, 1992; Costa-Cabral & Burges, 1994; Tarboton, 1997). Here the portion of accumulated upslope area which each downhill cell i receives from one upslope cell is weighted with respect to the slope gradient $\tan\beta_i$ between the upslope cell and cell i (Quinn *et al.*, 1991). As proposed by Freeman (1991) and Holmgren (1994), the strength of this weighting can be adjusted by a varying exponent h . With $h = 1$, the index calculation corresponds to the multiple flow direction algorithm of Quinn *et al.* (1991); for large values of h (e.g. $h = 100$) the computations approach to a single flow direction algorithm, with all the upslope area being routed to the cell in the steepest downhill direction (O'Callaghan & Mark, 1984).

In the original index calculation algorithms (Quinn *et al.*, 1991), flow accumulation occurs continuously to the catchment outlet, not taking into account cells containing a channel. Nevertheless, accumulated flow may enter a channel and be exported from the catchment without contributing to the development of saturated areas in downhill cells. Therefore, a channel initiation threshold, cit , (Quinn *et al.*, 1995) was tested. A cell with an upslope area exceeding cit , and all following downslope cells in the direction of the steepest gradient, are marked as channel cells. Accumulated area routed downslope from a channel cell is assumed to equal cit at the most, with the surplus of upslope area being considered to contribute to the channel.

The topographic index in the study area was calculated for about 140 different combinations of h and cit , with these parameters varying in the range of $1 < h < 100$ and $30\,000\text{ m}^2 < cit < 500\,000\text{ m}^2$.

Comparison of the spatial distribution of the topographic index with field observations reveals the necessity of characterizing locations in the field by their average soil moisture status. Seasonally or event-dependent variations must be excluded, just as the topographic index is a measure of average conditions of one cell relative to its neighbours. Therefore, pedological and geobotanical mapping criteria were developed in order to achieve a consistent delimitation of areas with specific average soil moisture characteristics over the entire research basin. Areas were mapped as saturated areas if they showed hydromorphic characteristics in the entire soil profile and a predominance of wetness indicating plants as classified by Ellenberg (1991).

Comparisons of mapped saturated areas with the spatial distribution of the topographic index were carried out considering the following criteria:

- Visual comparison of mapped saturated areas with the spatial pattern of the index.
- Visual comparison of maps of saturated areas with maps showing the location of cells with the highest 6.8% index values (the portion of mapped saturated areas was 6.8% of total basin area, see results).
- The threshold index value I_e that was exceeded by 6.8% of all cells was computed for each combination of h and cit . Data layers of the index pattern and of mapped saturated areas were transformed to a common $10\text{ m} \times 10\text{ m}$ raster data structure. When overlaying both grids, the percentage p of mapped saturated area, that coincided with index values greater than I_e , could be computed.

Settlement areas were excluded from analysis.

STUDY AREA

The mountainous Brugga basin (40 km^2) is located in the southern Black Forest, southwest Germany. It is characterized by a high relief intensity; altitude ranges between 440 and 1496 m a.m.s.l. with a mean slope of 17.5° . Three typical topographic units can be distinguished: narrow valley bottoms (5% of total basin area), steep slopes of the valley margins (75%) and hilly upland areas (20%). Bedrock consists of gneiss, covered by (peri-) glacial debris of varying depth. Mean annual precipitation is about 1750 mm; mean annual runoff amounts to 1250 mm. The main part of the basin, especially in steep areas, is forested, whereas valley bottoms and uplands are widely used as pasture. The portion of settlements is small, approximately 3% of the total basin area.

RESULTS AND DISCUSSION

6.8% of the total basin area (not including settlements) was mapped as saturated area (Fig. 1). Transitions to places with no wetness indicating characteristics could be observed within a very short distance. Many saturated areas are located along rivers in the main valley bottoms or in hollows of cirques of Pleistocene origin, for instance. In addition, numerous saturated areas were found on steep slopes or close to the watershed divide (Fig. 1). At a rough visual check, the pattern of high index values was in satisfactory correspondence with the location of the mapped saturated areas. However, various regions with saturated areas which were not reflected in the index pattern were apparent.

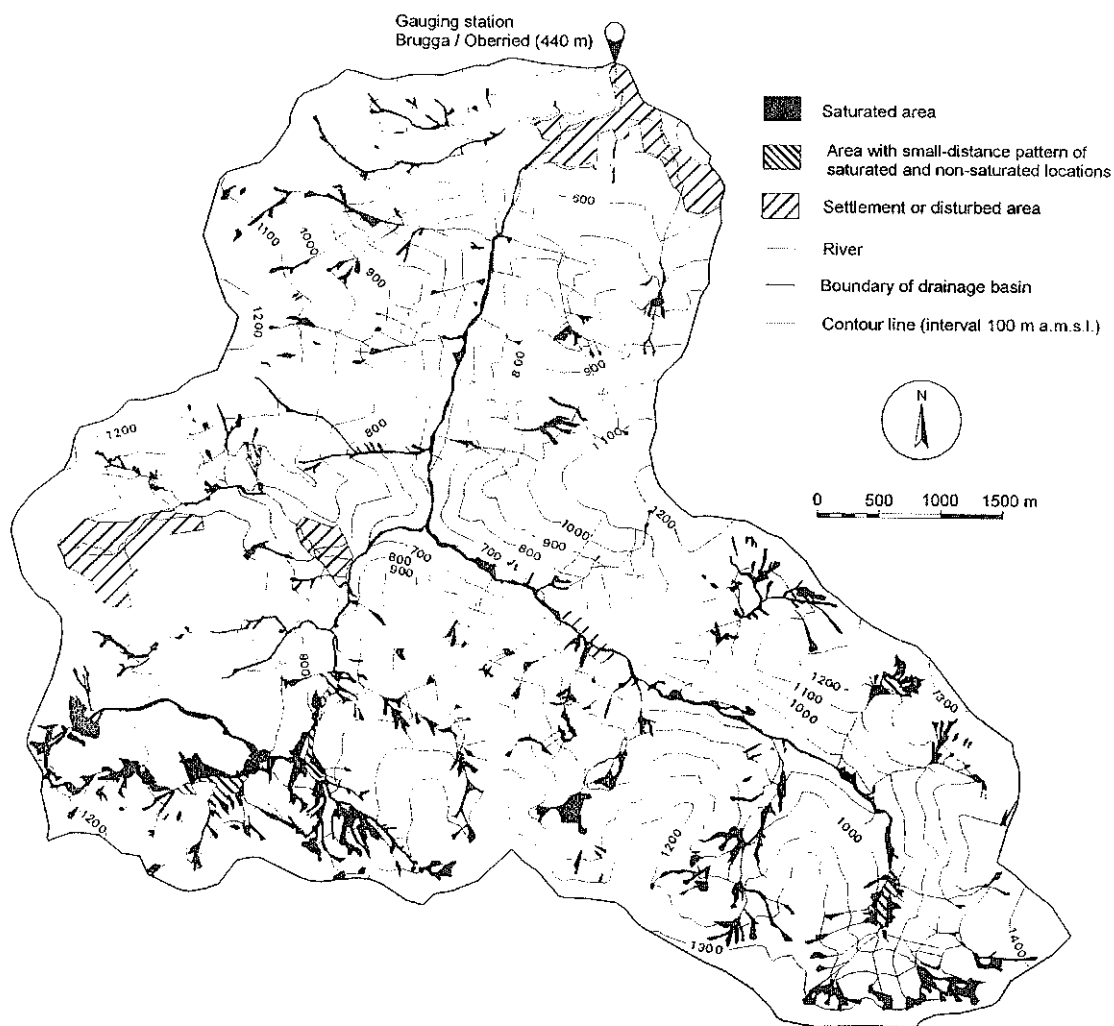


Fig. 1 Spatial distribution of saturated areas in the Brugga basin.

Looking closer, notable differences of spatial patterns and summary statistics of the different algorithms can be detected (Table 1, Figs 2, 3). The best parameterization for topographic index calculation in relation to the distribution of mapped saturated areas, according to the criteria mentioned above, was found with $h=10$ and $cit = 100\,000\text{ m}^2$. The improvement, when comparing to the classical multiple or single

Table 1 Comparison of characteristics of the topographic index distribution for a multiple flow direction algorithm (a), single flow direction algorithm (b), and the method best corresponding to mapped saturated areas in the Brugga basin (c).

	h	$cit\ (\text{m}^2)$	I_e	$p\ (\%)$	maximum I	median I	mean I
(a)	1	–	10.02	32.3	20.58	6.67	7.15
(b)	100	–	9.36	31.4	20.58	6.25	6.63
(c)	10	100 000	8.97	34.5	14.98	6.32	6.55

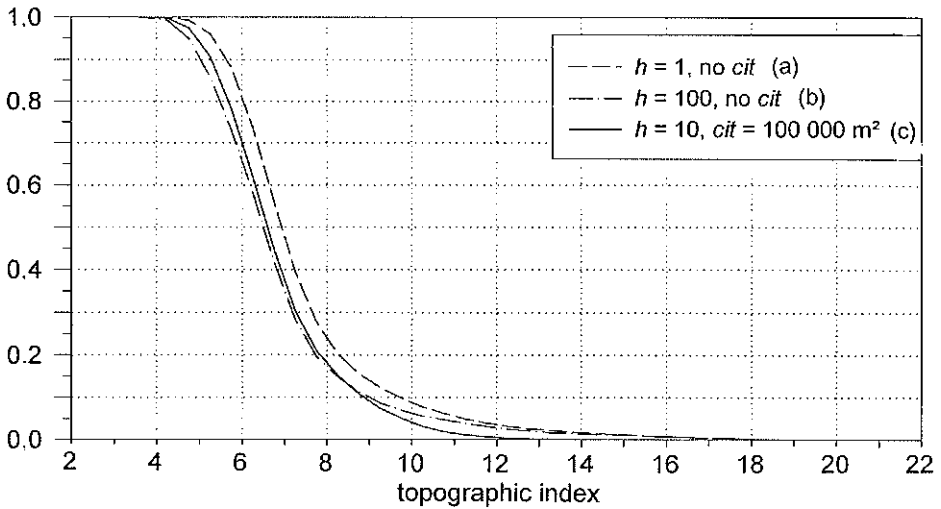


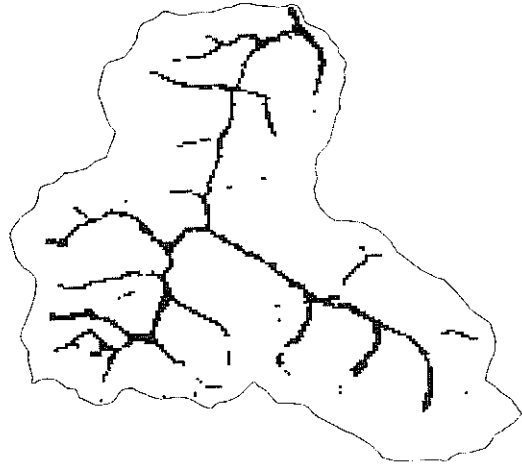
Fig. 2 Cumulative frequency distribution of the topographic index in the Brugga basin calculated with (a) multiple flow direction algorithm, (b) single flow direction algorithm, (c) method best corresponding to mapped saturated areas.

flow direction algorithms, was small in terms of p (Table 1), but a markedly better visual adaptation to mapped areas could be achieved in this way.

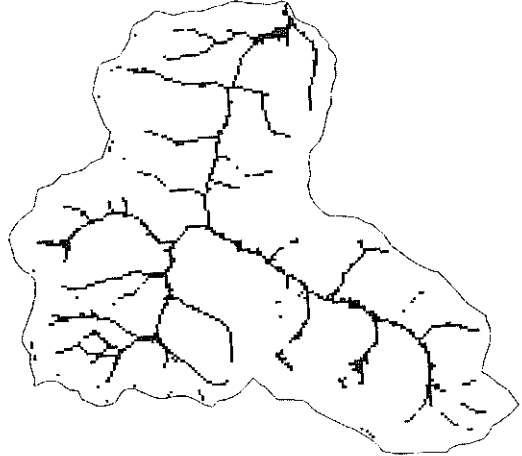
A weighting exponent $h > 1$ produced more converging flow patterns (Holmgren, 1994), leading to more confined bands of higher index values in valley bottoms along the main rivers when compared to the multiple flow direction algorithm with $h = 1$. Therefore, a greater portion of higher altitude or some steeper sloped cells contributed to the 6.8% largest cell values (Fig. 3). This corresponded well with field mapping, where saturated areas in valley bottoms are often aligned only near the rivers and numerous saturated areas can be observed in the upper parts of the Brugga basin. Setting $h = 10$, i.e. a compromise in between the classical single and multiple flow direction algorithms concerning flow concentration, yielded the best results (Fig. 3).

The introduction of the channel initiation threshold cit resulted in an important improvement of the index pattern. Previously high index values in the area of streams with steep slopes were reduced, due to the reduction of accumulated area being routed downslope when taking channel cells into account. Therefore, these cells were no longer part of the cells with the 6.8% highest index values (Fig. 3). This phenomenon was confirmed by field observations, where no saturated areas could be found adjacent to streams, e.g. connecting upland areas over the steeply inclined sides of the main valleys with the valley bottoms (Fig. 1). Furthermore, by taking into account channel cells for index calculation, very high index values towards the catchment outlet disappeared in favour of index values similar to those in higher elevated valley bottoms. This was also in accordance with the field observations, as no difference could be observed between saturated areas near the catchment outlet and higher elevated ones. Thus, regarding the topographic index as an index of hydrological similarity (e.g. Beven *et al.*, 1995), the consideration of channel cells is an important feature, as it reduces a bias in index calculations especially in larger basins. A value of $100\,000\text{ m}^2$ for cit was found to give the best results in comparison to mapped saturated areas. Lower values of cit produced too many channel cells and, therefore, index values were reduced in a too large part of the basin, whereas higher values of cit

(a) $h = 1$, no *cit*



(b) $h = 100$, no *cit*



(c) $h = 10$, *cit* = 100 000 m²

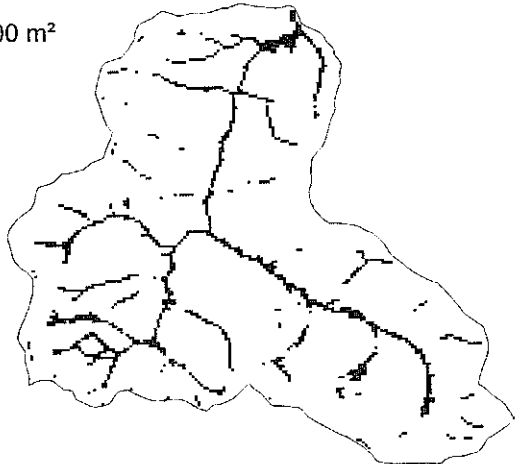


Fig. 3 Spatial distribution of cells with the 6.8% highest values of the topographic index in the Brugga basin calculated with (a) multiple flow direction algorithm, (b) single flow direction algorithm, (c) method best corresponding to mapped saturated areas.

resulted in an insufficient occurrence of the effects of channel cells mentioned above. It must be noted, that the optimum value of cit is largely dependent on the grid size of the digital elevation model used (Quinn *et al.*, 1995). The river network created with $cit = 100\,000\text{ m}^2$ corresponded well to its representation on topographic maps of scale 1:50 000, though this was not the criteria for the estimation of cit .

Only about one third of all mapped saturated areas agreed with topographic index values above the threshold value I_c . The small values of p (Table 1) indicating a poor agreement of mapped saturated areas with high index values, pointed out some deficiencies in the methods used in this study and some general limitations of the topographic index for the regionalization of saturated areas in the study area. Besides inaccuracies in the delimitation of saturated areas during field mapping, fundamental difficulties when comparing data layers with originally differing data structures (topographic index and saturated areas with raster and vector types, respectively) may have contributed to the low values of p . In addition, the grid resolution of 50 m used for index calculation was too coarse to reflect adequately the small-scale pattern of mapped saturated areas. Subgrid topographic features, particularly significant in the steeply sloped Brugga basin, could not be represented.

Furthermore, the assumptions (especially uniform transmissivity and recharge) underlying the concept of the topographic index, will not be valid in the study area. Occurrence of compact till deposits in some parts of the Brugga basin increase the tendency for waterlogging and formation of saturated areas. The assumption of uniform recharge is not valid because of varying climatic conditions due to the large range in elevation of more than 1000 m. The increase of precipitation is indicated by a greater portion of saturated areas in the higher elevated zones of the study area (Fig. 1). Characteristic patterns of mapped saturated areas, that are not represented by high index values, emphasize the significance of factors other than topography in the generation of saturated areas. Their occurrence on steeply inclined slopes indicates the existence of springs at fractures of the crystalline bedrock. The widespread appearance of saturated areas at a certain distance below the top of valley margins (Fig. 1) can be attributed to a strata boundary between massive crystalline bedrock and overlying debris cover. These geological factors can obviously not be represented by an index taking into consideration only topography.

CONCLUSIONS

When testing various methods for calculation of the topographic index based on grid digital elevation models, differences of the respective spatial distributions and statistics were stressed. Thus, using the topographic index for spatially distributed studies, the selection and discussion of an appropriate algorithm is essential. Field observations yielded valuable support in this regard, particularly as the mapped information covered a large area in this study. Important features of the spatial pattern of the saturated areas could finally be represented by the index distribution. The most suitable values of h and cit will be specific to the grid resolution used and the study area, but further studies may provide more general advice for selecting an appropriate method.

The resolution of the digital elevation model with a cell size of $50 \times 50\text{ m}^2$ was able to produce a pattern of high index values, which corresponded well with the

mapped saturated areas at the basin scale. At a local scale, however, this resolution was found to be too coarse to adequately reflect their location in the steeply sloped drainage basin. Comparisons of the field survey with the topographic index distribution reveals some weakness in the application of a simple topography-based concept for estimation of saturation excess overland flow areas in the study area. Other factors like geology, spatially variable transmissivity or climatic conditions must be taken into consideration. Thus, the need for an extended index is corroborated by this study. Finally, for modelling of saturation excess overland flow, differing hydrological reactions of saturated areas have to be evaluated, taking into account their varying characteristics (saturated areas adjacent to streams, saturated areas in hollows of springs, mires, etc.), including event dependent and seasonal dynamics.

In general, the concept of the topographic index requires a critical review with respect to calculation algorithms and characteristics of the study area before its application as a tool for the regionalization of hydrological properties. Validation against observed field patterns provides the best route forward.

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