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Modeling spatial patterns of saturated areas: A comparison of the topographic wetness index and a dynamic distributed model

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SUMMARY

Topography is often one of the major controls on the spatial pattern of saturated areas, which in turn is a key to understanding much of the variability in soils, hydrological processes, and stream water quality. The topographic wetness index (TWI) has become a widely used tool to describe wetness conditions at the catchment scale. With this index, however, it is assumed that groundwater gradients always equal surface gradients. To overcome this limitation, we suggest deriving wetness indices based on simulations of distributed catchment models. We compared these new indices with the TWI and evaluated the different indices by their capacity to predict spatial patterns of saturated areas. Results showed that the model-derived wetness indices predicted the spatial distribution of wetlands significantly better than the TWI. These results encourage the use of a dynamic distributed hydrological model to derive wetness index maps for hydrological landscape analysis in catchments with topographically driven groundwater tables.

Introduction

The spatial pattern of saturated areas, including wetlands and lakes, is a key characteristic of boreal landscapes and a factor controlling variables such as stream water quality (Ågren et al., 2007; Cory et al., 2006), land–atmosphere feedback mechanisms (Nilsson et al., 2008) and landscape ecology (Petrin et al., 2007; Serrano et al., 2008). Manual mapping of soil moisture patterns is costly, labor-intensive, and not feasible at large scales. Remote sensing approaches are often useful, but difficult to apply in forested landscapes (Creed et al., 2003), limited to the upper most soil layer and usually require calibration when mapping soil moisture (Houser et al., 1998).

Topography provides an alternative for mapping wetlands and spatial patterns of wetness in catchments where the assumption that groundwater tables basically follow topography holds (Haitjema and Mitchell-Bruker, 2005). The topographic wetness index (TWI) (Beven and Kirkby, 1979) relates upslope area as a measure of water flowing towards a certain point, to the local slope, which is a measure of subsurface lateral transmissivity. The TWI has become a popular and widely used way to infer information about the spatial distribution of wetness conditions (i.e. the position of shallow groundwater tables and soil moisture). On the other hand, the TWI is static and relies on the assumption that local slope, $\tan(\beta)$, is an adequate proxy for the effective downslope hydraulic gradient which is not necessarily true in low relief terrain. In flat terrain, the local slope has a tendency to overestimate the downslope hydraulic gradient due to the effect of downslope water tables. The TWI concept is also less suitable in flat areas because of rather undefined flow directions which are more likely to change over time. In situations where meteorological and hydrological data are available in addition to a digital elevation model (DEM), a more dynamic approach might be useful. Distributed hydrological models allow dynamic simulations of spatially distributed water storage that can be used to derive alternative wetness indices. These model-based wetness indices (MWIs) account, unlike the static TWI, for dynamic influences of upstream and downstream conditions. Thus, they are also applicable in flat terrain where groundwater gradients can be significantly different from ground surface slopes.

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Several studies have discussed the TWI concept and its underlying assumptions (Barling et al., 1994; Seibert et al., 2002) as well as the need for an improved representation of downslope effects and variable contributing areas. For instance, Crave and Gascuel-Odoux (1997) point out the importance of downslope topographic conditions for the spatial distribution of surface wetness, which was one of the motivations for Hjerdt et al. (2004) to develop a downslope index that better represents local groundwater gradients. Barling et al. (1994) and Borga et al. (2002) focus on the size of the effective upslope contributing areas. They introduce a 'quasi-dynamic' wetness index for a better estimation of upslope contributing areas under non-steady state conditions (Barling et al., 1994; Borga et al., 2002). The idea of deriving MWIs from the state variables of a dynamic distributed hydrological catchment model is to find an alternative approach that integrates the effects of downslope controls and variable upslope contributing area. In principle, any moisture-related, spatially-distributed state variable of a catchment model can be used to derive dynamic wetness indices by temporal aggregation.

Important characteristics of simulated time series can be described by statistical moments. As an example, one can compute both mean and standard deviation of simulated, distributed groundwater levels. In this paper, we focus on the comparison of MWIs with the TWI and, thus, we use only MWIs that were computed as long-term averages of simulated groundwater levels.

The objective of this study is to evaluate different MWI and TWI variants by assessing their ability to predict the patterns of saturated areas in a boreal catchment. Saturated areas represent the extreme end of the landscape wetness spectrum and, thus, spatial patterns of saturated areas provide an opportunity for evaluating different methods for mapping not only saturated areas but also landscape wetness in general. The underlying assumption is that a method that represents well the extreme end of the wetness spectrum might also work well at drier locations (Rodhe and Seibert, 1999).

We used two different distributed hydrological models (Grabs et al., 2007) to derive two MWIs from dynamic model simulations as well as from a steady-state MWI (MWI_{steady}). The latter was based on a distributed model but in this case, the model is run using temporally constant meteorological forcing. For comparison, we computed the TWI in two different ways. This allowed us to answer a number of questions: Can model-based wetness indices (MWIs) provide significantly better results than the standard TWI? How does the effect of using MWIs to predict wetlands compare to the effect of using different algorithms for computing TWI? How do dynamic MWIs compare to a steady-state MWI that does not require detailed meteorological forcing data and still allows overcoming the limitations of TWI?

Material and methods

Study site and measurements

The study was conducted on the upper 67 km^2 of the Krycklan catchment (64°14′N, 19°46′E) in northern Sweden. The catchment ranges from 126 to 369 m above sea level and is underlain by poorly weathered gneissic bedrock. In the upper part of the catchment, above the highest post-glacial coast line, glacial till deposits up to 10 m deep were left by the last glaciation. Below the highest post-glacial coast line, coarse-grained glaciofluvial deposits and fine-grained silty or sandy sediments have allowed the streams to form deeply incised channels that efficiently drain the surrounding landscape. Wetlands, which are generally sphagnum-dominated, have formed mainly in areas with flat, drainage-limiting topography and cover about 9% of the catchment area (Buffam et al., 2007). The most common soils in the catchment are well-developed iron podsols. Along the stream network, histic soils or gleysoils can be found. Most of the landscape is forested with Scots pine (*Pinus sylvestris*). Deciduous trees such as birch (*Betula* spp.) or alder (*Alnus incana*) are found in wetlands and along streams, while

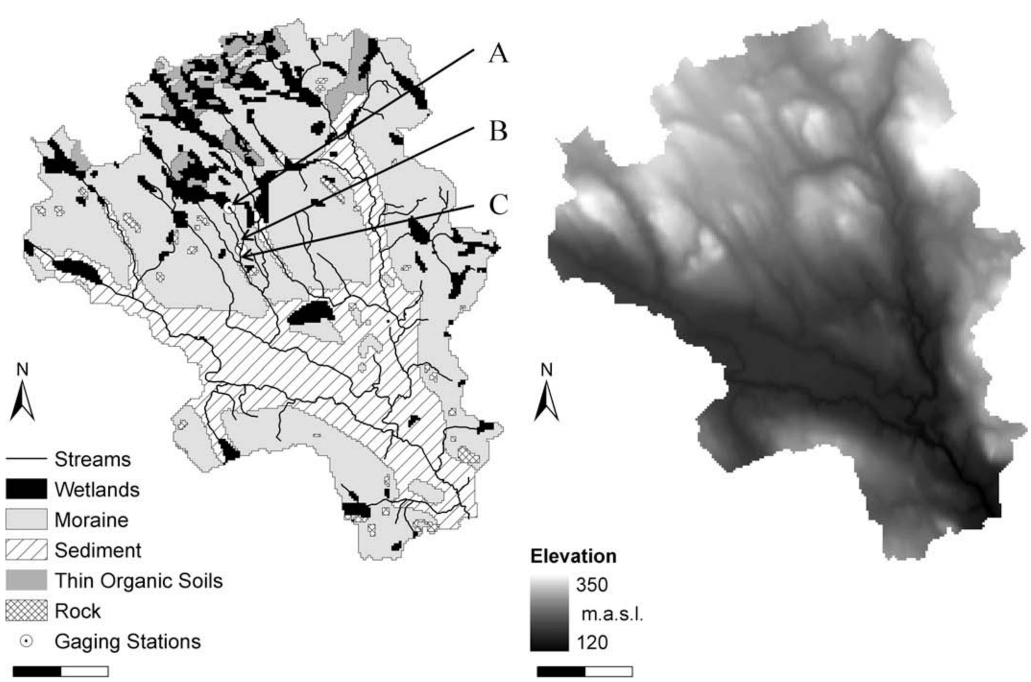

Fig. 1. On the left: Geologic features and location of gaging stations and streams in the Krycklan catchment. Wetland cluster in the upper, flat till parts of the catchment. Flow rates measured at the outlets of Kallkällsmyren (A), Västrabäcken (B) and Kallkällsbäcken (C) were used for model fitting. Västrabäcken (B) lies directly upstream the junction of the creeks from Västrabäcken (B) and Kallkällsmyren (A), whereas Kallkällsbäcken (C) lies downstream of it. On the right: Elevation map of Krycklan. Flat areas in the upper part can be distinguished as patches with relatively uniform grey shades.