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Evaluation of a surface hydrological connectivity index in agricultural catchments

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ABSTRACT

Identification of surface hydrological connectivity at scales where critical source areas (CSAs) can be managed is fundamental to achieving effective management of phosphorus loss in agricultural catchments. This study investigated the potential for the 'Network Index' (NI) to predict surface connectivity at CSA-management scales in contrasting agricultural catchments (*ca.* 1200 ha) using a 5 m DEM. One catchment had mostly permeable soils and a low surface ditch density. The other catchment had mostly impermeable soils and a high surface ditch density. The importance of surface ditch data for accurately modelling the location and magnitude of surface connectivity was also evaluated. Modelled surface connectivity at the subcatchment scale (*ca.* 130 ha) was validated using observed channel (ditch and stream) densities. Modelled surface connectivity at the field scale (*ca.* 2 ha) was evaluated using four indicators of observed field connectivity. At the subcatchment scale, modelled surface connectivity matched observations well ($R^2 = 0.52$) despite the soil type variability across catchments. However, some errors in subcatchment boundary delineation (total of 133 ha in one catchment) occurred which could distort the extent of predicted CSAs. At the field scale, the NI had potential for broadly discerning the most connected from the least connected fields which is valuable for identifying where CSA-based management should be targeted. Detailed ditch information was required to accurately delineate subcatchment boundaries; however, it was not needed for predicting subcatchment connectivity.

Software availability

Program title: SAGA
Developers: J. Böhner and O. Conrad
Contact Address: University of Hamburg, institute for Geography, Bundesstraße 55, 20146 Hamburg, Germany
First Available: 2004
Hardware: Windows/Linux
Source Language: C++
Program Size: 4.2 MB
Cost: GNU General Public License
Availability: http://sourceforge.net/projects/saga-gis/
Program title: SCIMAP
Developers: Sim Reaney and David Milledge
Contact Address: Department of Geography, Durham University, UK
First Available: 2005
Hardware: Windows/Linux
Source Language: C++
Program Size: 349 KB
Cost: Creative Commons license
Availability: http://www.scimap.org.uk/SCIMAP-2011-and-saga2.0.zip

1. Introduction

Characterising hydrological connectivity in rural catchments may provide potential for mitigating diffuse nutrient pollution from agriculture by facilitating the identification and targeted

Abbreviations: CSA, Critical source area; NI, Network Index; TWI, Topographic Wetness Index.

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management of critical source areas (CSAs). These areas are where nutrient rich sources have a high propensity for connection to receiving water bodies via effective transport pathways. As phosphorus is generally primarily transported in surface or near surface flow (Haygarth and Jarvis, 1999), delineating CSAs for phosphorus loss requires accurate characterisation of the hydrological connectivity of surface flowpaths. Connectivity is a relatively new concept in hydrology and hydrological connectivity still remains poorly defined. Nevertheless, it is widely acknowledged that hydrological connectivity encompasses two key aspects; the spatial distribution of connected zones such as saturated areas, and the magnitude (both frequency and duration) of the connections (Wainwright et al., 2010).

A variety of modelling approaches have been used to characterise hydrological patterns and processes relevant to diffuse nutrient pollution. Commonly used physically-based approaches, derived using multiple datasets include SWAT, HSPF and SHETRAN/GOPC (Nasr et al., 2007) and INCA-P (Wade et al., 2002). Popular terrain index approaches derived from surface topography include the Topographic Wetness Index (TWI) (Beven and Kirkby, 1979) and its derivatives (Guntner et al., 2004; Sørensen et al., 2006) and TopManage (Heathwaite et al., 2005). However, few approaches for modelling hydrological controls relevant to nutrient fluxes have incorporated elements of connectivity beyond representations such as distance of a field to a waterbody (Magette, 1998) or depth to groundwater (Buczko and Kuchenbuch, 2010). Reaney et al. (2007) have recently incorporated an element of connectivity into the fully distributed process-based CRUM model. However, whilst fully distributed process-based models, such as CRUM, may offer a good representation of the spatial complexity of hydrological processes within catchments, they are usually very data intensive and computationally demanding. Terrain indices offer great promise for connectivity modelling as topography is the easiest parameter to be measured at high resolution. The Network Index (NI) proposed by Lane et al. (2004) develops upon the TWI to offer a simple topographic approach to characterise hydrological connectivity. The TWI is defined as ln ($\alpha/\tan\beta$) where α is the local upslope area draining through a certain point per unit contour length and $\tan\beta$ is the local slope. It is a useful tool for describing the relative propensity for saturation within a catchment where saturation excess overland flow is the dominant runoff generating mechanism (but not for infiltration excess overland flow – e.g. Doody et al., 2010). The NI approach is based on the concept that the lowest (driest) value of TWI along flowpaths between points in the landscape and the stream is likely to reflect the greatest potential for infiltration of surface water along those flowpaths and therefore limits the degree of surface connectivity to the stream. The NI identifies the lowest value of TWI along a flowpath to the stream and assigns this value to each new cell encountered upstream along the flow path until a lower TWI value is encountered (Fig. 1b). The NI thus identifies wet and connected parts of the landscape. Connectivity is represented by the probability that lower NI values are likely to be connected less frequently and for shorter periods of time than higher NI values (Lane et al., 2009).

The NI is typically applied using digital elevation models (DEMs) of terrain. The potential for the NI to accurately predict surface connectivity, therefore, depends on the degree to which topography controls the location and magnitude of surface connectivity in the landscape. Non-topographic controls include soil type and artificial subsurface drainage.

Network Index accuracy also depends on the degree to which features that control the location and magnitude of surface connectivity are captured by the underlying DEM. Micro-topographic features such as surface ditches influence the *location* of surface connectivity by capturing and re-routing surface flow along the

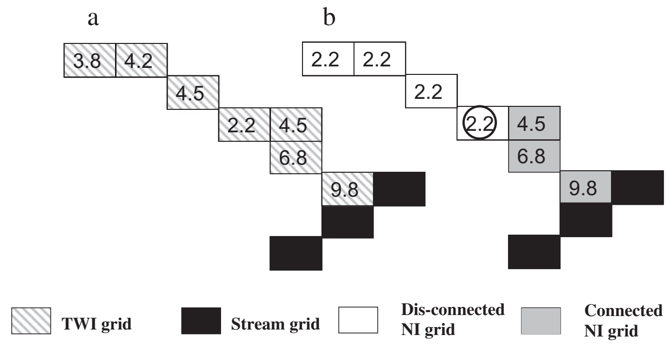

Fig. 1. Comparison of a) the propensity for saturation predicted using the TWI, and b) the propensity for connection of saturated areas using the NI, for a hypothetical flowpath to a stream. Higher values indicate higher propensity in both cases. The grid cell circled in black in (b) illustrates the lowest value of TWI along the flowpath to the stream. The white grid cells in (b) show where the TWI and NI values differ.

channel (ditch and stream) network and away from its natural flowpath. Digital elevation models which are not of sufficient spatial resolution to capture ditch features, therefore, may not accurately represent the location of surface connected flows. Inaccurate representation of the location of the channel network can lead to poor delineation of surface flow subcatchment boundaries, which are fundamental to utilisation of the NI to predict the extent of CSAs.

Surface ditches can have a dual effect on the *magnitude* of surface connectivity in the landscape. Ditches can increase surface connectivity in upslope fields by reducing the path-length to the channel network (Lane et al., 2004; Dunn and Mackay, 1996). Conversely, ditches can decrease surface saturation and connectivity in downslope fields by re-routing upslope surface flows along the channel network instead of downslope. However subsurface flows which bypass ditches would still contribute to downslope surface saturation. In surface-flow driven landscapes, where ditches re-route a large proportion of total flows, any increases in connectivity due to reduced path-length to the channel network are likely to be small relative to decreases in downslope connectivity caused by re-routing of surface flows. Insufficient capture of ditch features in the underlying DEM may result in a failure to re-direct surface flows and cause over-estimations of surface saturation in landscapes where surface flows are prevalent. Thus when applying the NI (or the TWI), the optimum topographic resolution of the underlying DEM may depend on the relative contribution of surface and subsurface flows to the development of surface saturation.

The NI approach has been applied to catchments in the United Kingdom where it has supported work related to prediction of sediment associated diffuse pollution (Reaney et al., 2011; Reid et al., 2007) in catchments ranging from 2 km^2 to 2310 km^2 and therefore it offers a promising approach for facilitating identification of CSAs in agricultural catchments. Thus far, the NI approach for modelling surface connectivity has only been tested by comparison to predictions of a physically based distributed hydrological model for an impervious catchment with homogeneous soil drainage (Lane et al., 2009).

The objective of this study was to evaluate the potential for the NI to predict surface connectivity using field observations in agricultural catchments where surface ditches are prevalent and at spatial scales relevant for informing best phosphorus management on farms. It was hypothesised that:

(i) The accuracy of NI predictions of surface connectivity will be poor in landscapes with variable soil types.