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Representation of landscape hydrological connectivity using a topographically driven surface flow index

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[1] This paper assesses the extent to which a topographically defined description of the spatial arrangement of catchment wetness can be used to represent landscape hydrological connectivity in temperate river catchments. A physically based distributed hydrological model is used to characterize the space-time patterns of surface overland flow connection to the drainage network. These characterizations are compared with a static descriptor of the spatial structure of topographically controlled local wetness, called here the Network Index. Theoretically, if topography is the primary control upon hydrological response, the level of catchment wetness required to maintain connectivity along a flow path should be greater for flow paths that have a lower value of the topographically controlled local wetness. We find that our static descriptor can be used to generalize a significant proportion of the time-averaged spatial variability in connectivity, in terms of both the propensity to and duration of connection. Although the extent to which this finding holds will vary with the extent of topographic control of hydrological response, in catchments with relatively shallow soils and impervious geology our index could improve significantly the estimation of the transfer of sediment and dissolved materials to the drainage network and so assist with both diffuse pollution and climate change impact studies. The work also provides a second reason for the concept that there are Critical Source Areas in river catchments: these arise from the extent to which that material can be delivered to the drainage network, as well as the generation of risky material itself.

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1. Introduction

[2] Not all locations in a river catchment, even if they have the same land use, contribute equally to the delivery of sediment or nutrients and hence in-stream sedimentation and water quality degradation [*Gburek et al.*, 2000; *Heathwaite et al.*, 2000; *Quinn*, 2004; *Lane et al.*, 2008]. Rather, certain areas have been shown to be critical sources, where the ability both to entrain material and to connect it to the drainage network controls the level of delivery [*Cammeraat*, 2002; *Ambroise*, 2004; *Beven et al.*, 2005]. Diffuse nutrient and sediment issues can be redefined as comprising a series of point sources (i.e., fields, or even parts of fields) where particularly risky land uses combine with a high probability of connection of those risks to the river system [*Lane et al.*, 2006, 2008]. In this paper, we focus upon connection by overland flow pathways. This type of connection appears to be conditioned by local, often sub-field-scale, hydrology [e.g., *Blackwell et al.*, 1999; *Burt et al.*, 1999; *Western et al.*, 1999, 2001; *Lane et al.*, 2004; *Quinn*, 2004; *Heathwaite et al.*, 2005], in some cases related to quite subtle topographic attributes (e.g., Figure 1). However, diffuse land management signals emerge over much larger spatial scales, as a result of the integration across the landscape to the drainage network of these finer-scale processes.

[3] This scale issue represents an immediate challenge for hydrological modeling, and the management of diffuse drivers of in-stream water quality and ecological degradation in particular, as well as for capturing the impacts of processes like climate change upon future stream processes. The dominant approach to profiling diffuse pollution risk is based upon use of simple empirical transfer functions. These translate known fertilizer and manure inputs, coupled with soil nutrient status [e.g., *Jordan et al.*, 1994; *Johnes*, 1996; *Heathwaite et al.*, 2003; *Herrmann et al.*, 2003; *Ekholm et al.*, 2005] into an estimate of the amount of material that is exported from a land unit. Such functions may be extended to include physically based models of nutrient cycling in individual land units in order to improve the estimation of export [e.g., *Priess et al.*, 2001; *Weber et al.*, 2001; *Binder et al.*, 2003; *Wolf et al.*, 2005; *Matthews*, 2006; *Vatn et al.*, 2006]. While there remain unresolved issues with these kinds of models, much less attention has been given to the role played by hydrological connectivity in delivering generated material to the river network. The most simplified approaches have no real treatment of connectivity at all, as in the Soil Conservation Service Curve Number method used in various models [e.g., *Beasley et al.*,

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Figure 1. Sub-field-scale soil erosion and the role of a small-scale (<25 m^2) surface hollow in causing disconnection. Source: Eden Rivers Trust.

1980; *Savard*, 2000; *Weber et al.*, 2001; *Galbiati et al.*, 2006]. Basic attempts to recognize the effects of connectivity have been introduced, such as through weighting delivery according to the distance of a land unit from the nearest water course [e.g., *Johnes and Heathwaite*, 1997; *Munafo et al.*, 2005], or in a more sophisticated way, such as a function of downslope distance from a water course [e.g., *Childress et al.*, 2002]. Physically based, distributed models, which solve for both the vertical and lateral flux of water across the landscape have also been developed [e.g., *Adams et al.*, 1995; *De Roo and Jetten*, 1999]. However, these models tend to lose much of the spatial detail of what we know about which areas of the landscape are most likely to be Critical Source Areas because they are commonly applied [e.g., *Adams et al.*, 1995] at scales (up to 1 km^2) coarser than those that are likely to control connectivity, typically <0.0025 km^2 (e.g., Figure 1). There are two related reasons for this coarse scale of application. The first is that these models are exceptionally demanding in terms of parameterization (e.g., see *Merritt et al.* [2003] for review) The information demands of model calibration often exceed available data [*Heathwaite*, 2003; *Harris and Heathwaite*, 2005] even given improvements in data acquisition and assimilation, and the models are rarely parsimonious with respect to the data available to determine them.

[4] The second comes from the computational difficulty of running such models with time steps that are small enough to capture the dynamics of catchment response and spatial resolutions that can capture the heterogeneous structure of the topography of drainage basins. Figure 1 shows how, over a very small distance, there is a substantial difference between required process representations; here between a channelized rill type flow and more diffuse, potential, overland flow. Representing such process gradients with small spatial scales (<0.0025 km^2) in very large river basins (>1000 km^2), with a time dependence, remains a challenge. Historically, hydrological analyses have assumed that the physical representation in a model should take dominance over the spatial discretization of that model, with the result that models with physics developed for small spatial scales (e.g., Darcy's law) are applied over very large spatial units (e.g., 1 km^2 [*Adams et al.*, 1995]), even though heterogeneity within those units undermines critical assumptions, such as uniform water table slope, upon which those physics depend. As Figure 1 shows, the scale of unit that controls delivery of eroded sediment is, in this case <0.0025 km^2. For situations where topographic detail exerts an important control upon hydrological response, new technologies, notably airborne laser altimetry and interferometric SAR have been shown to be of sufficient quality for hydrological analysis [e.g., *Milledge et al.*, 2009]. This provides an imperative to reevaluate the norms of hydrological analysis under the assumption that the physical representation adopted in a hydrological model should be commensurate with the spatial representation of the process gradients that the model aims to represent. This is not an argument against using physically based models but rather a recognition that the level of physical simplification in the model should be parsimonious with both the data available to represent them and the processes that are to be represented.

[5] We have been approaching this problem by exploring how to incorporate sufficient of what we know about the physics of hydrological connection, in this case by overland flow, into diffuse pollution models. As part of this research, we have obtained a surprising result in terms of the role played by topography in controlling surface hydrological connectivity. It opens up a wealth of new ways of thinking about diffuse land management risks in river catchments that allows a much stronger hydrological input to diffuse pollution modeling. The focus of this paper is connectivity by surface overland flow in temperate upland environments associated with shallow soils. We conceptualize connectivity as being driven by the propensity to generate saturated overland flow (SOLF), which expands and contracts in space and time [e.g., *Beven and Wood*, 1983]. As this occurs, so possible sources of land management risk are tapped, becoming Critical Source Areas [*Heathwaite et al.*, 2000]. In this paper, we test the role played by topography in controlling SOLF generation and subsequent connectivity by comparing an index-based representation of connectivity, the Network Index, with predictions from a physically based, distributed, hydrological model. The paper begins with a theoretical reformulation of the Network Index as an index of hydrological connectivity by surface overland flow, then explains the methodology we used to test this reformulation, and finally discusses the implications of the results obtained as well as the limitations of the findings of the analysis.

2. Theoretical Formulation of the Network Index as an Index of Hydrological Connectivity

[6] The topographic index [*Kirkby*, 1975] is commonly used as a measure of the relative propensity for a point in the landscape to develop saturation and, if saturation is controlled by topography alone, locations with the same value of the topographic index should have the same hydrological response. The topographic index uses the ratio of the area drained per unit contour length (the upslope contributing area) to the tangent of the local slope. However, research has shown that the degree of spatial organi-

zation of soil moisture limits the effectiveness of this index [e.g., *Western et al.*, 1999] primarily because the topographic index assumes steady state drainage conditions, which is a necessary assumption for a terrain-based determination of the upslope contributing area [*Barling et al.*, 1994]. Subsequent research has reformulated the topographic index to have a dynamic component based upon the notion of an effective contributing area [e.g., *Barling et al.*, 1994; *Grayson et al.*, 1997; *Piñol et al.*, 1997]. The approach we adopt in this paper is similar to *Piñol et al.*'s [1997] and is based upon the concept that local soil saturation deficits control when a noncontributing area begins to contribute, at least for shallow soils. However, we set this deficit as a result of an implicit analysis of terrain rather than introducing it as an explicit model parameter. In this application, we do not specify any spatial variation in transmissivity and hence are assuming a uniform, shallow (<c. 1.0 m) soil type.

[7] Under these assumptions, the lowest value of the topographic index along the flow path that connects a point on a hillslope to the drainage network should control the connectivity of that point to the drainage network by surface overland flow. *Lane et al.* [2004] call this the Network Index. Points with higher values of the Network Index will connect more readily with the drainage network. *Lane et al.* [2004] determined the Network Index using a 2 m resolution digital elevation model acquired using airborne laser altimetry to show that not only were runoff source areas in an upland catchment variable in time and space but, and crucially, not all source areas were hydrologically connected to the drainage network even in extreme storm events. The key driver of this was local topographic variability at scales of 20 m or less.

[8] The Network Index is a static descriptor of the propensity to surface hydrological connectivity. Aside from the assumptions above, its relevance to hydrological connection can be challenged by the observation that connectivity will be crucially controlled by storm event duration [*Bracken and Croke*, 2007]: the delivery of material from a point in the landscape to the river channel within a storm event will require a longer storm event the further the point is away from the river channel along the associated flow path. There are two conditions that lead to disconnection. Type 1 disconnection occurs where material is moving along a flow path during a storm event, but reaches a point along that path that becomes dry before it reaches the drainage network. Type 2 occurs where the event is of insufficient magnitude and duration to wet the driest point along a flow path, such that the material reaches a dry point before it reaches the drainage network. In terms of the transfer of material across the landscape, the significance of disconnection depends upon the parameter being considered. For a physically conservative parameter that cannot infiltrate significantly into the soil column (e.g., fine sediment), it will be deposited at the surface and remain there until a subsequent entrainment event and associated surface hydrological transfer, unless contaminants are attached to it that are soluble. It is probable that sites of disconnection are zones of temporary material accumulation until the associated connection condition is met. It may also mean that understanding connection and disconnection without reference to the spatial structure of probable disconnection along a flow path is not possible. For a nonconservative parameter, these processes will be further complicated by the possibility that it will change. For a dissolved parameter, subsurface hydrological connection will become important.

[9] Given these observations, there are logical limits to using the Network Index to describe hydrological connection. However, the question remains as to how much information the Network Index contains about hydrological connection. Thus, there are three hypotheses that we test in this paper. First, points that are drier will require a larger rainfall event for them to connect upstream flow paths to the river network. Thus, when integrated through time, they are more likely to limit connectivity by surface overland flow. Hence, whether or not a point can ever connect with the drainage network by surface overland flow could be controlled by the Network Index, with the probability of connection being greater for higher values of the Network Index. Second, although the Network Index is a static descriptor on the basis of spatial attributes, it should implicitly contain a temporal component in terms of the number of times that there is likely to be connection through points that limit connectivity. The number of times a point will connect will be greater for higher values of the Network Index. Third, if the number of times a point connects is greater, the duration of connection should be greater. The caveat to this is that for points along a given flow path which share the same Network Index (i.e., the same downstream connection-controlling point), those further up the flow path are likely to have lower durations of connectivity as a result of Type 1 disconnection.

3. Methodology

[10] The methodology has two components: (1) use of a distributed hydrological model and extraction of information to test these hypotheses regarding hydrological connectivity and (2) description of the catchment that we applied the connectivity index to, including an explanation of how it was applied.

3.1. Physically Based, Distributed Modeling of Catchment Hydrology

[11] In order to test these hypotheses, we have generated high-frequency spatially distributed maps of soil moisture status, and hence saturation, from which we can determine whether or not points in the landscape are connected, how many times within a given integration period and for what duration. This has been done using CRUM2D v. 3.1, a fully distributed, physically based hydrological simulation model which has a similar basis to that described by *Reaney et al.* [2007] and *Conlan et al.* [2005]. As these types of models are well established in the literature, details of the model are provided in the auxiliary material and only a summary is provided here.[1]

[12] The landscape is represented using a grid structure coupled with a separate river channel network model. In each landscape cell, the hydrological processes of interception, infiltration, evapotranspiration, throughflow and recharge to groundwater are simulated. Evapotranspiration is simulated using the Priestley-Taylor [*Priestley and Taylor*, 1972] method. Infiltration is modeled with the simplified

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008WR007336.

Green and Ampt [1911] model of *Kirkby* [1975] which relates the infiltration rate to the soil moisture. Throughflow is determined using Darcy's Law. Soil depth is allowed to have a simple topographic dependence and the saturated hydraulic conductivities in both the root zone and the soil, and the decay of the latter with depth, are set as parameters. The water is routed through the river channel network using the Muskingum-Cunge algorithm [*Ponce and Lugo*, 2001]. The model has a variable time step, defined by the rate of change of internal hydrological variables, ranging from 2 min through to 6 h, and this allows minimization of the amount of time required for long (annual and multiyear) simulations.

[13] For this research, a set of indices which describe the spatial and temporal dynamics of surface hydrological flows have been developed, aided by the grid structure of the model and noting that the model itself does not make any prior assumptions about the nature of flow connectivity. Mirroring the definition of the Network Index, we note that for a point to be considered connected, it must not be subject to a Type 2 disconnection: there must be overland flow along the complete flow path to the river channel. This allows us to determine (1) whether or not a point on the landscape connects during a given period; (2) the number of times it connects; and (3) the percentage of time that the cell is connected completely along a flow path, mirroring the hypotheses we are aiming to test. Using the hydrological model to determine Type 1 disconnection is more complex as it requires tracing of generated runoff in time and space, something that is not possible with the current formulation of the model. We emphasize that these determinands are a property of the model, and not necessarily of the landscape that the model is describing, such that our evaluation of the static descriptor is effectively a determination of how much information is lost in the description of catchment connectivity by using a static descriptor with a simplified underlying physical basis.

3.2. Case Study Catchment, Determination of the Network Index, and Application of the Physically Based Model

[14] In this paper, we apply the model to the Upper Rye catchment in North Yorkshire, United Kingdom. The Upper Rye catchment is a 13.1 km^2 catchment comprised of grassland and moorland (Figure 2). For both the Network Index and application of CRUM2D, we use a 20 m resolution DEM, derived from the NEXTMap® data for Great Britain. Derived values of the Network Index were rescaled to a Relative Network Index (RNI). The scaling was linear between 0 and 1. Although our analysis is based upon a single case study catchment, it is one that has two very contrasting geological and topographical settings (Figure 2), broadly defined as the eastern and western subcatchments, which allow us to explore both the form of the representation at the level of the whole catchment and the two subcatchments. The eastern subcatchment comprises Oolitic sandstones and the western subcatchment Cordillerian limestones.

[15] CRUM2D was used in two ways. First, it was applied using spatially variable land cover information as part of model parameterization. The latter was based upon a Generalized Likelihood Uncertainty Estimation [*Beven and Freer*, 2001] using (1) random sampling of 3,000 parameter sets for the dominant parameters that controlled model response; (2) determination of the best parameter sets that resulted in independence between two Objective Functions (the Nash Sutcliffe Efficiency and the Relative Mean Absolute Error) used for model evaluation (see auxiliary material); and (3) identification of the range of model parameters associated with these parameter sets, labeled here as the behavioral parameter sets. The model reproduces the measured discharge hydrograph well for these parameter sets (Figure 3): for the majority of the time, the measured value is bracketed by ± one standard deviation of model predictions. The minimum value of the Nash Sutcliffe Efficiency [*Nash and Sutcliffe*, 1970] for these simulations was 0.655 and the maximum Mean Absolute Discharge Error was 0.29 $m^3 s^{-1}$, around 10% of base flow discharge, the latter defined as the discharge for which 95% of flows are greater. This means that CRUM2D is capturing at least some elements of the landscape's hydrological response, even though we have no further data to test the hypothesis that it is describing aspects of the internal hydrological response of the system. In methodological terms, this means that if the hydrological model descriptions of connection do not match those of the static descriptor, it could be because the internal process representation in the hydrological model is not right. However, if they do match, then some confidence should be gained in both. We emphasize, as described above, that the hydrological model has a physically based time- and space-dependent, process representation (see auxiliary material) which includes representation of both (1) at-a-point hydrological response, in terms of evapotranspiration, soil moisture dynamics, and (simultaneously in response to rainfall intensity and soil moisture state) different mechanisms of overland flow generation; and (2) lateral routing of water, both over the surface and through the subsurface.

[16] In order to determine the surface hydrological connectivity indices for comparison with the Network Index, a parameter set was randomly sampled from the behavioral parameter sets but with the land cover set to be uniform, so as to provide a meaningful comparison with the assumptions associated with the Network Index. Even with the use of a single parameter set, determination of the connectivity indices was extremely demanding in terms of data handling and analysis. For this reason, the model was run for the three wettest sample years, sampled from the 30 year period from 1961 to 1990.

4. Results

[17] Figure 4 is based upon a binary discriminator as to whether or not a cell is connected completely along a flow path during the hydrological model run. The RNI of each cell is then used to sort this binary discriminator. The binary discriminator is then cumulated, scaled by the number of sites and plotted against the RNI. This represents the probability that the site is a connecting site as defined by the RNI. If the RNI were a perfect discriminator of connection and disconnection, and given that 47.7% of sites connected during the 3 years of hydrological model simulations, we would expect an RNI value of 0.523 to be a perfect discriminator between sites that do not connect (<0.523) and sites that do connect (≥ 0.523), with a vertical line centered on 0.523. The curve for the full catchment shows that the RNI is positively associated with probability

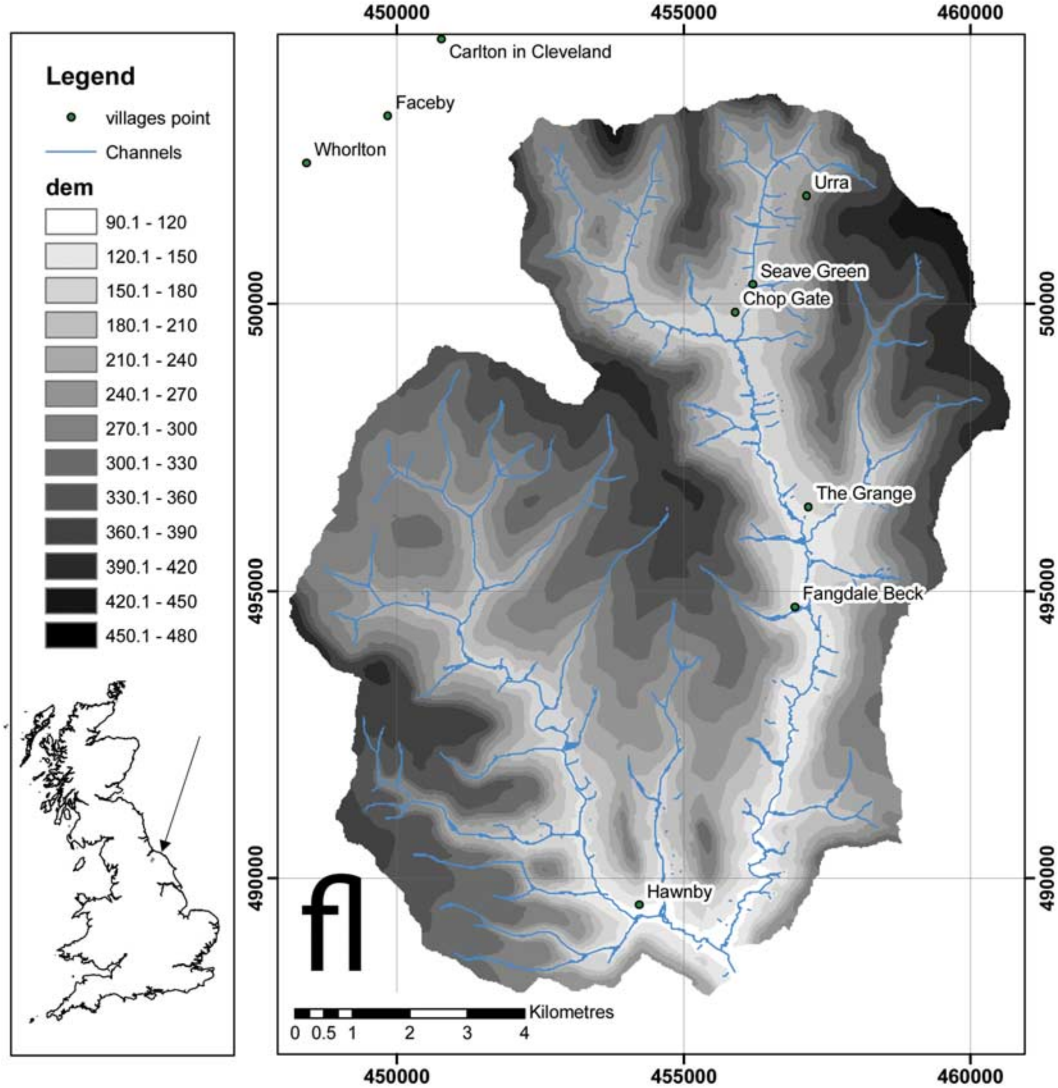

Figure 2. NEXTMap digital elevation model of the Upper Rye catchment. United Kingdom outline is Crown Copyright Ordnance Survey. An EDINA Digimap/Joint Information Systems Committee–supplied service. Crown Copyright/database right 2009. An Ordnance Survey/EDINA-supplied service.

of connection. Its mapping onto perfect discrimination (i.e., the horizontal) is better for lower and higher values of the RNI: only a very small percentage of locations with the lowest values of the RNI do actually connect; although a larger percentage of locations with the highest value of RNI do not connect (Figure 4). The curve also separates data points into the western and eastern subcatchments to obtain some sense as to the effects of different geological and topographical controls within the catchment. This suggests that the RNI better discriminates connecting sites for the eastern subcatchment than the western subcatchment, although the differences are relatively small, reaching a maximum difference in probability of 0.08.

[18] Figure 5 shows a probability density function for the RNI plotted against the logarithm of the duration of connection, the latter scaled on the longest modeled connection; 200 bins are used. The full catchment (Figure 5a) and the eastern and western subcatchments (Figures 5b and 5c, respectively) are shown. Figure 5a shows that not only does the RNI contain information on the probability of connection, it also contains information on the duration of hydrological connection. For RNI values less than 0.5, connection durations are negligible. For RNI values greater than 0.5, there is a clear trend for Relative Index values to have progressively longer connection durations. Given the transformation applied to the connection access, the duration of connection increases as an exponential function of the RNI. Comparison of the eastern (Figure 5b) and western (Figure 5c) subcatchments shows differences that are similar to, but clearer than, those suggested for connection probability (Figure 4). The shapes of the plots for the eastern and western subcatchments are similar. However, for the eastern catchment (Figure 5b), the RNI is more strongly associated with the log-transformed connection duration that for the western subcatchment (Figure 5c): the RNI values at which there is the onset of much longer connection durations is clearer; above this threshold, the RNI is more strongly associated with the log-transformed correction duration; and the slope defined between RNI and log-transformed correction is less steep, such that extrapolation through to

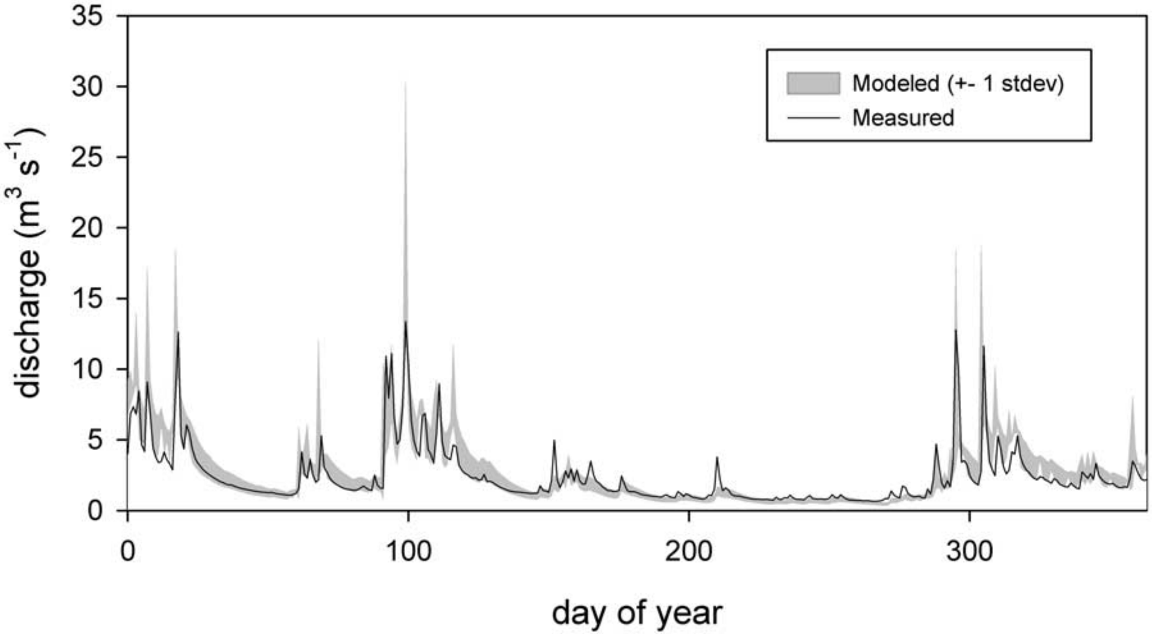

Figure 3. Measured and modeled discharge for the Upper Rye catchment, North Yorkshire, United Kingdom. The chart shows the mean and the ± one standard deviation of the behavioral simulations.

RNI = 1 would result in longer connection durations in the eastern subcatchment.

[19] Figure 6 shows the RNI map for the studied catchment. This shows that the Relative Network Index has a number of distinct spatial scales of variability. In the western subcatchment, draining through Hawnby (Figure 2), there is a marked large-scale difference between the high levels of connection in the north of the subcatchment and along the subcatchment's west and southwest boundaries and the low levels of connection in the south of the subcatchment (Figure 6). High levels of connection tend to be clustered upon the stream heads (Figure 6), most clearly along the subcatchment's west and southwest boundaries. The spatial extent of individual well-connected areas is also greater in the north of the subcatchment (Figure 6). In the south of the subcatchment, well-connected areas, which can have a very high level of connection, are much smaller in their spatial extent and tend to be closer to the mainstream.

[20] In the eastern subcatchment, there is less evidence of any large-scale structuring of connection into broadly well connected or poorly connected regions, with the possible exception of the eastern side, where levels of connection are higher along the headwater streams of the far eastern edge (Figure 6), in ways not dissimilar to the western edge of the western subcatchment. Rather, variations in connectivity tend to have a much finer spatial scale of variability than in the western subcatchment (Figure 6). Also, and crucially, locations of high connectivity tend to be located closer to the mainstream, the opposite of the dominant characteristic in the western subcatchment, where high-connectivity areas were associated with the stream heads.

5. Discussion

[21] These results allow us to assess the three hypotheses identified above. First, despite the RNI being a static spatial

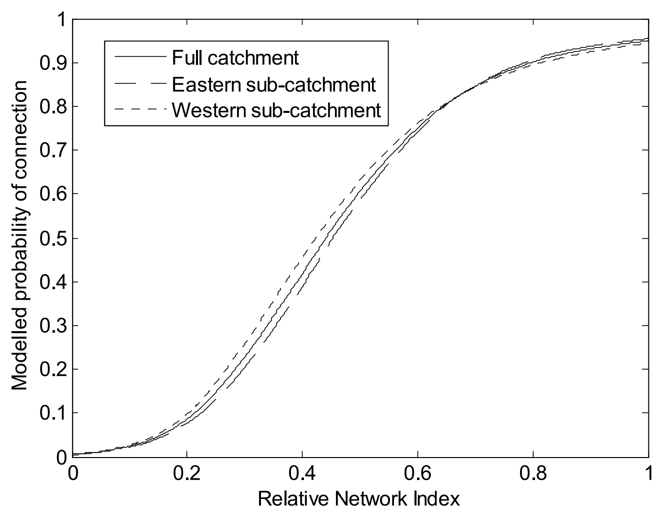

Figure 4. The cumulative probability that a site is a connecting site as defined by the RNI: if the RNI were a perfect discriminator of connection and disconnection and given that 47.7% of sites connected during the 3 years of hydrological model simulations, we would expect a RNI value of 0.523 to be a perfect discriminator between sites that do not connect (<0.523) and sites that do connect ($\geq$0.523), with a vertical line centered on 0.523. Probabilities >0 for RNI <0.523 are sites that do connect during the time period but are not expected to given their RNI; probabilities <1 for RNI $\geq$0.523 are sites that do not connect during the time period but would be expected to given their RNI. Curves are shown for the full catchment and the eastern and western subcatchments (see Figure 2).

metric, it enables us to infer whether or not a site connects. Following from Figure 4, and in the absence of other information, this can be expressed as a probability that a site connects, for the range of storms modeled using the hydrological model, for a given value of the RNI. The form, if not the detail, of this relationship does not differ significantly between the two main subcatchments. In terms of diffuse pollution and soil erosion studies, this could provide the first means of incorporating a terrain sensitive measure of connectivity likelihood in a risk framework, without recourse to full physically based modeling, and informed by a basic hydrological conceptualization rather than arbitrary weights like distance from nearest water course. Such modeling would need to address how the form of this curve changes with respect to the duration of integration (e.g., monthly, yearly, decadally) and with catchments with different relief and soils and in relation to possible climate change impacts.

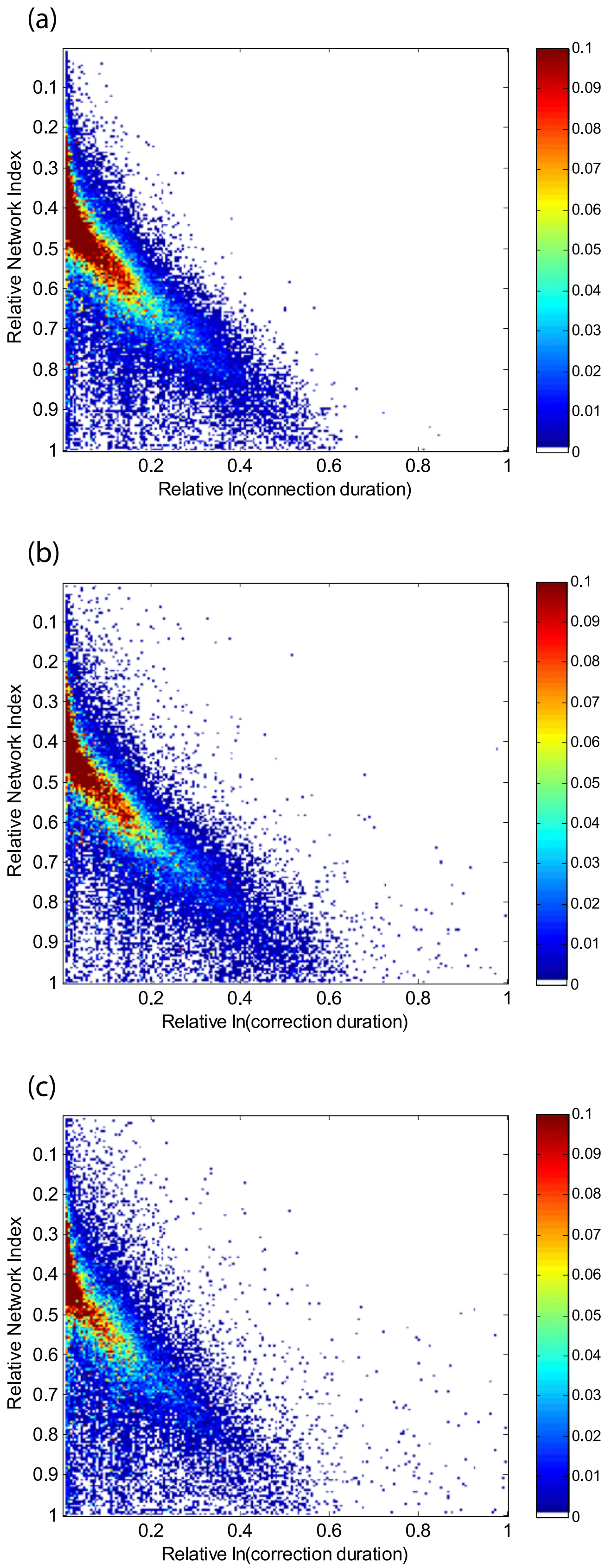

Figure 5. The relationship between the RNI and the logarithm of the duration of connection scaled by the maximum modeled connection time. This is shown as a two-dimensional probability density function with 0.05 width probability bins. (a) The full catchment and the (b) eastern and (c) western subcatchments (see Figure 2).

[22] Second, and perhaps more surprisingly, the Network Index metric appears to capture some of the temporal dynamics of connectivity (Figure 5): negligible connection durations below the RNI of 0.5 followed by an exponential increase in connection duration for values greater than this. Again, the shape of this relationship is similar between subcatchments, but the detail differs, with a stronger association in the eastern subcatchment. Although the definition of disconnection adopted is Type 2, it is probable that those connection durations associated with RNI values less than 0.5 are unlikely to be sufficient for the delivery of material, and that the RNI may also be representing Type 1 processes, although it is important to acknowledge the complexity of the delivery process [*Beven et al.*, 2005] that means that the representation is partial. Locations with a higher Network Index are connected for longer, and the spatial signal of topographically induced wetness results in partial control of the dynamics of surface overland flow connectivity and potentially delivery. Thus, the surprising finding in this paper is that a static descriptor derived from the spatial structure of topographically controlled local wetness is capable of predicting at least some information on the likelihood, frequency and duration of connection.

[23] Plot-scale studies of the ways in which hillslope elements connect to the drainage network may identify connections that deviate from topographical control, as is reflected in this study by the scatter present in Figure 5. Our results are unusual in showing that, despite such deviations, and through using a numerical model to provide a description of connectivity that provides information on the entire river catchment, a generalizable landscape attribute can be identified in the absence of other influencing factors. When judged at the catchment scale, the importance of topography for hydrological response has been shown to dominate over soil transmissivity [*Wood et al.*, 1990], and while we do not explore transmissivity effects herein, the study confirms the importance of topography in determining the spatial structure of landscape connectivity. The work emphasizes the care that must be shown in inferring from plot-scale studies the relative importance of connectivity at the landscape scale as this importance can only be judged with respect

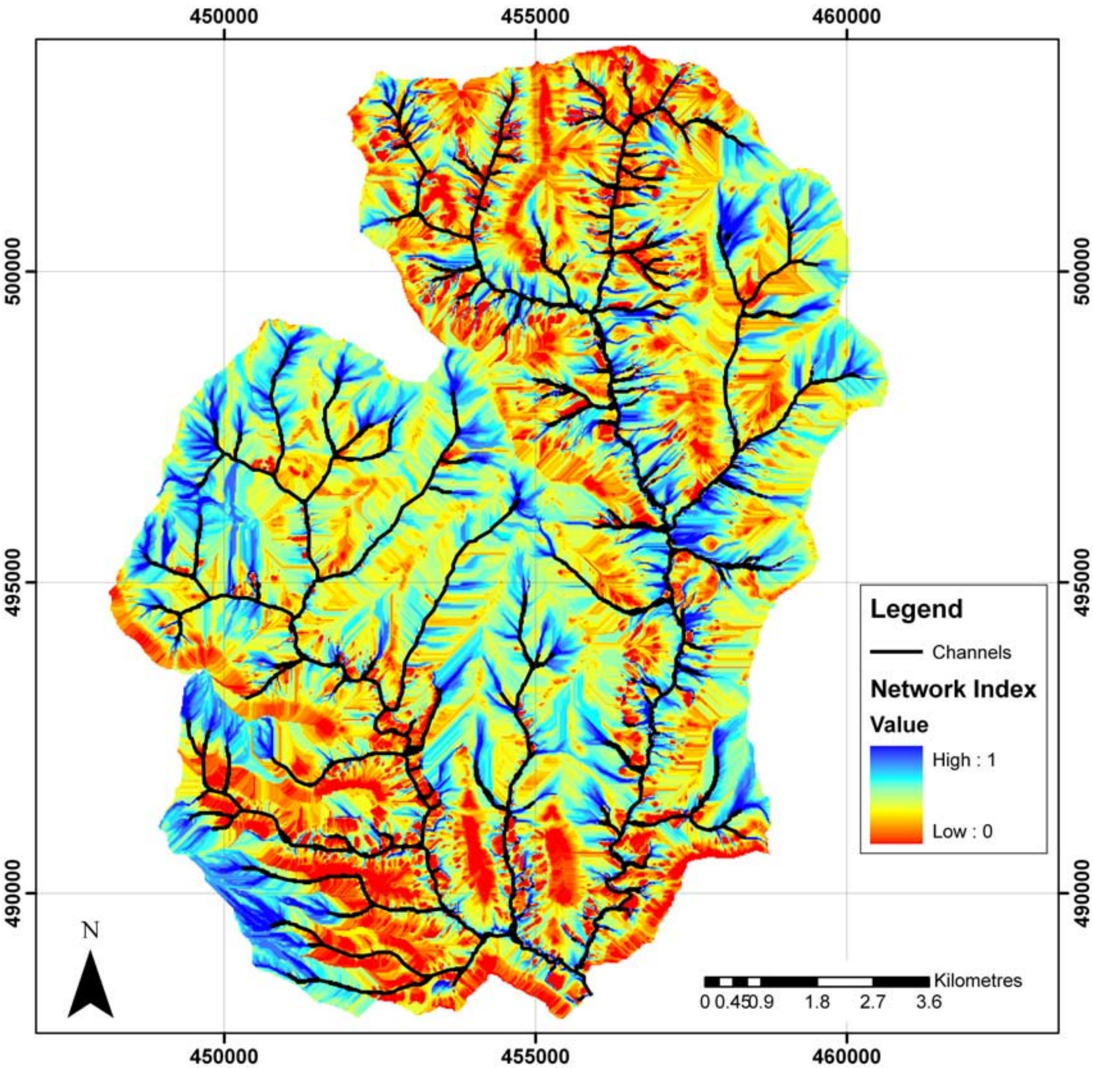

Figure 6. Map of the Relative Network Index for the study area.

to both local topography and the wider topographic setting defined by the associated flow path to the drainage network. It is particularly important for processes associated with diffuse land management where their impact upon locations in the drainage network derives from integration over a potentially large area.

[24] The identification of a connectivity metric of this form opens up the possibility of thinking about the hydrological function of landscapes in hitherto unexplored ways. The RNI is a property of surface topography. As a catchment wets up, the RNI at which there is connection will fall. Rather than leading to the continuous expansion and contraction of saturated zones as is implied in the traditional model of topographically controlled saturation, it implies that potentially large landscape units become connected as a result of control by a potentially small number of geographically localized landscape units. These units are ones where, in relative terms, the flux of water is vertical rather than lateral. *Grayson et al.* [1997] conceptualize the landscape as switching through time between periods when connectivity is poor as a result of dry antecedent conditions and leading to vertical fluxes being dominant and periods when connectivity is dominated by lateral flux. Herein, we conceptualize the landscape as switching between lateral and vertical flux along a flow path. We implicitly assume that the locations along a flow path where vertical fluxes are most likely to be dominant, in this case on the basis of a network-scale analysis of the topographic index, are those that are most likely to break up surface flow connectivity. Although specifically formulated (and evaluated herein) for surface overland flow, the analysis ought to apply equally for shallow subsurface flows and fluxes of material in terms of vertical versus lateral fluxes.

[25] Previous work on effective contributing area [e.g., *Barling et al.*, 1994; *Grayson et al.*, 1997] still leaves our analysis with a problem. The RNI is a contradiction in the sense that it uses a traditional topographic index derived from the upslope contributing area per unit length, identifies the lowest value of the topographic index along a flow path, and then argues that this location controls the connectivity of points upstream of this location. Until this cell is connecting upstream areas, locations downstream should be assigned a much smaller effective contributing area. Thus, the analysis has a bias: locations closer to the channel may be assigned an artificially inflated upslope contributing area, and be more able to connect as a result. It is surprising

that this is not manifest in the form of a larger number of locations that have a high RNI but that never actually connect (Figure 4). Further, topography need not be the only reason why the effective contributing area may be different to a terrain-defined contributing area. For instance, *Aryal et al.* [2003] demonstrate how evaporation along a flow path prevented the development of saturation at the bottom of a hillslope. As *Western et al.* [1999] note, analysis based upon terrain indices should be based on considerations of the actual processes occurring in a particular catchment under a particular climate. Thus, while Figure 4 suggests that a static analysis of terrain can be transformed into a probabilistic estimate of the likelihood of connection, this will only be the case where the primary control on connectivity at the landscape scale is topography. Further research is needed to explore whether the shape of the curve can be generalized between catchments and in situations with different and/or heterogeneous land cover characteristics.

[26] The effective contributing area bias aside, the result also goes some way to explaining why simple empirical transfer function models of diffuse pollution, which weight delivery according to distance from the river channel, do well as compared with what we know about the complexity of catchment hydrological response. They capture part of the process described here: as the distance from a water course along a flow path increases, so the probability of the RNI value being lower will increase. To describe the connection between the material exported from a land unit and its delivery to the river channel, a detailed representation of hydrological function may not be necessary [*Quinn*, 2004]. The work also shows how simple conceptual models about where to focus diffuse pollution remediation measures (e.g., on catchment heads) themselves need to be questioned: the data in Figure 6 show how that the zones of high connectivity and hence high risk can vary regionally and over different spatial scales within the same catchment. The identification of a topographically driven control upon landscape hydrological connectivity also means that, as global change studies move to the consideration of climate change impacts upon catchment function, simple models, applied at the resolution at which catchments connect hydrologically, may be more important than models with a strong physical basis, but whose computational requirements or data availability requirements necessitate application at scales much coarser than those associated with hydrological response.

6. Conclusion

[27] We have compared the information on the spatial patterns of hydrological connectivity revealed by continuous simulation using a physically based, distributed hydrological model with a static descriptor of surface hydrological connectivity based upon the spatial structure of the topographic index of wetness. The latter is justified by the observation that the ease of connection by surface overland flow will be controlled by the extent to which lateral surface flux is dominant throughout a flow path. The lowest value of the topographic index along a flow path is assumed to be the point at which vertical fluxes, and hence the propensity to disconnect, will be greatest. The lower the lowest value of the topographic index along a flow path, the greater the level of catchment wetness required to cause water table rise to the point at which lateral flux can be maintained. This provides a theoretical rationale for the idea that the temporal patterns (propensity, duration) of connection might be captured using a static descriptor based upon the spatial structure of topographically driven wetness. Comparison with the results from continuous simulation shows that significant spatial variability in both the propensity to connection within a time period, as well as the duration of that connectivity, can be explained using this metric. Although specifically formulated (and evaluated herein) for surface overland flow, the analysis ought to apply equally for shallow subsurface flows and fluxes of material in terms of vertical versus lateral fluxes, although this needs to be tested for a wider range of catchment types. Critically, this provides a hydrologically informed measure of the propensity and duration of connection that might become the basis of more plausible analysis of the risks arising from diffuse land use activities where, to date, the characterization of hydrologically driven delivery processes tends to be exceptionally poor.

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