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Modelling water and sediment connectivity patterns in a semi-arid landscape

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ABSTRACT

Desertification is a major threat in SE Spain and mitigation strategies are required to reduce the adverse effect of water-induced erosion on soil production potential. Severity of soil erosion depends on local runoff response and the connectivity of pathways of water and sediment at different spatial scales. We investigated the connectivity between sources and sinks on semi-natural slopes by means of a semi-distributed model that delineated Hydrological Response Units (HRUs) on the basis of physiographic characteristics. The model was calibrated with information at the plot, hillslope and sub-catchment scale covering the period 1995-2008 and validated against larger events that connected the semi-natural sub-catchment with the underlying cultivated slopes. This approach allowed us to define thresholds at which HRUs transform from sink to source and pathways of water and sediment connect at higher spatial scales. The recognition of the spatio-temporal behaviour of HRUs as sources and sinks is essential for the definition of efficient mitigation strategies that reduce erosion by intervening at strategic points within the catchment. The next step is to improve the skill of the model to reproduce erosive events and deposition over a longer period in the past with more variable meteorological and land cover conditions.

INTRODUCTION

Mediterranean semi-arid environments are very dynamic, having erratic climatic conditions and changing land use in response to shifting socio-economic constraints (Geeson et al., 2002). Variations in climate and land cover affect the vegetation cover that greatly affects runoff production and soil erosion rates (Thornes, 1990). Expanding human influence and agricultural developments put sustainable use of land and water under stress. Consequently, quantification of the hydrological response, soil erosion and sedimentation is vital to combat deterioration of soil production potential or desertification and foment sustainable use of natural resources. Not only the amount and reallocation of water and eroded material are of interest but also the distance over which they are being transported and where sink and sources or water and sediment occur. Connectivity patterns of hydrological pathways, either via diffuse or concentrated flow paths are very dynamic (Bracken and Crooke, 2007), and not only depend on the amount of rainfall, surface runoff, infiltration capacity and sediment supply, but also on thresholds related to vegetation structures and landscape structures (Cammeraat, 2004; Lesschen et al., 2009). As a result, vestiges of erosion processes often indicate very different intensities. The goal of this paper is to explore the scale dependent thresholds observed in runoff generation and the spatial distribution of runoff generating areas as well as connectivity against a simple dynamic semi-distributed GIS based model. Such models help to study the spatio-temporal patterns of soil erosion and to evaluate mitigation strategies that intervene in the management of strategic locations in the landscape.

METHODS

The catchment under study is located in the Guadalentín basin (SE Spain). It has a semi-arid climate with a mean annual rainfall of 270 mm and a relief between 550-650 m. Vegetation cover ranges between 20and 95% depending on exposition, bedrock and degradation status. Semi-natural vegetation is restricted to the steeper and more dissected slopes. Runoff from these slopes and catchments is used to feed rainfed agriculture on the broader plains of valley infills (Figure 1) Runoff and sediment measurements have been carried out since 1996 (See Imeson and Cammeraat (1999) and Cammeraat (2004) for site details). Estimates of net erosion losses centre on 0.4 tons·ha^{-1}.yr^{-1} for plots under natural vegetation. Net erosion rates for agricultural areas are generally low due to soil conservation measures but can be catastrophic in the case of extreme events when these measures fail and then may reach values far over 40 ton ha$^{-1.}$ (Cammeraat, 2004).

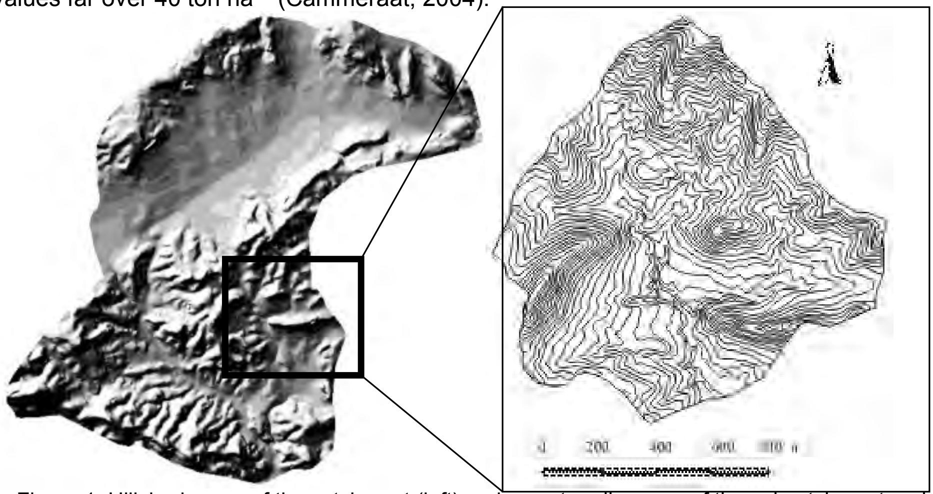

Figure 1. Hillshade map of the catchment (left) and a contour line map of the subcatchment under semi-natural vegetation (10m equidistance; right and inset in hillshade map).

A model simulating runoff generation and overland flow was developed in PCRaster (Wesseling et al., 1996). Existing data from the field site (Imeson and Cammeraat, 1999) as well as data from Dooms (2003) were used to tune the model for the catchment shown in Figure 1. Basic assumption of this model was the use and definition of Hydrological Response Units (HRU) (England, 1970, Busch et al.,1999) for the whole catchment area, based on substratum, exposition, soil degradation status and vegetation cover and structure (Figure 2). Each HRU is represented as a single point, corresponding to the cell with the lowest elevation, that has a threshold that has to be overcome before water and sediment pathways extend into the underlying HRU. This threshold is calculated from infiltration rate, precipitation, storage and loss by interception and surface roughness. Sink and source areas for water and sediment are delineated incorporating both the sink-source behaviour of the response unit itself as well as the water coming from its upslope units. The model parameters saturated hydraulic conductivity, Manning's n, soil storage capacity and canopy storage capacity were tested on sensitivity. The model is being tuned on the basis of field observations of runoff using runoff data from plots and sub-catchments and from runoff calculated via the Manning equation from high water marks in the larger channels at different locations within the catchment. At the moment, the information used represents two events at which pathways transcended different scales within the sub-catchment of Figure 1. Furthermore the spatial distribution of connectivity was checked against field observations of rill and channel flow. Calibration will be extended to more events in order to include the robustness of the model predictions of runoff generation and erosion and deposition.

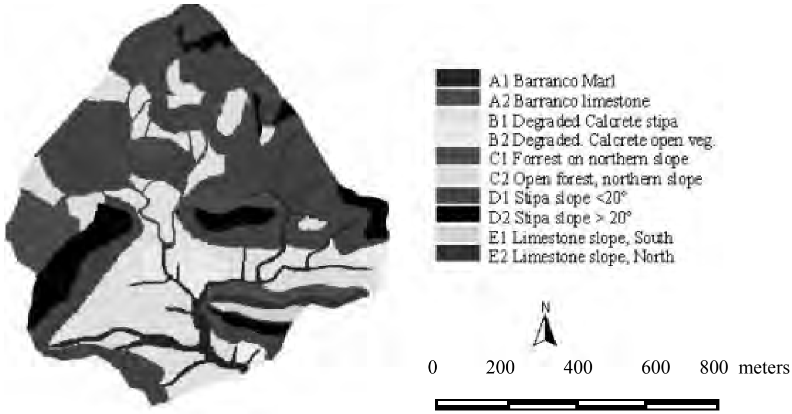

Figure 2: Spatial distribution of land units from which the hydrological response units were derived (from Dooms, 2003).

RESULTS AND DICUSSION

The model was most sensitive to the saturated hydrological conductivity that controls the ultimate infiltration capacity in the case of prolonged rainfall events. The second most sensitive parameter was the water storage capacity although sensitivity varied with the actual soil moisture status. With the limited information available, only a tentative fit of the simulated runoff with the observations could be made. Other than from the erosion plots no time series of runoff were available but the lag-time between precipitation and runoff was quite realistic at the broader scales.
The simulation showed that for the selected events runoff could be accommodated by the HRUs A1, A2, C1, D1, D2 and E2 that act as sinks if precipitation rates remain below 30 mm hr^{-1}. Above 30 mm hr^{-1}, already less than 2 minutes of rain leads to runoff generation, as the time to ponding is exceeded for all units. This agrees well with the observations for different events in the area (Cammeraat, 2004). The spatial distribution of modelled runoff patterns (Figure 3) also matched the observations well. Vegetation density plays major in the generation of runoff, as well as surface characteristics of the channels and bare areas. At low rainfall intensities runoff is restricted to bedrock channels and bare rock slopes, while water downstream is absorbed in the alluvial valley fill or dense vegetation zones respectively. At higher intensities overland flow occurs in all channels and rills, independent of the material and characteristics. Also hillslopes with less dense vegetation cover show runoff. However, sinks are still present where both the locally generated runoff as well as that from upstream units is absorbed. The pediment areas, both degraded and intact, become sources of runoff due to the limited buffer capacity of these shallow soils. The connectivity patterns indicate where runoff will concentrate and allow for the identification of erosion hotspots and strategic points for intervention, *e.g.*, by eco-engineering practices such as planting water and sediment buffering plants (de Baets et al., 2006; Hooke et al., 2007). The preliminary results presented here will be expanded to include erosion and deposition to study sources and sinks of sediment and to identify how sediment is cascading through the catchment and influencing sediment budgets over longer time scales

CONCLUSIONS

-A semi-distributed dynamic model is presented that is able to delineate runoff generating areas and concentrated flow paths in a semi-arid catchment under semi-natural vegetation.
-The model can be applied for identifying strategic points of runoff generation and accumulation that can be targeted by sustainable eco-engineering applications to reduce runoff to limit on site degradation.

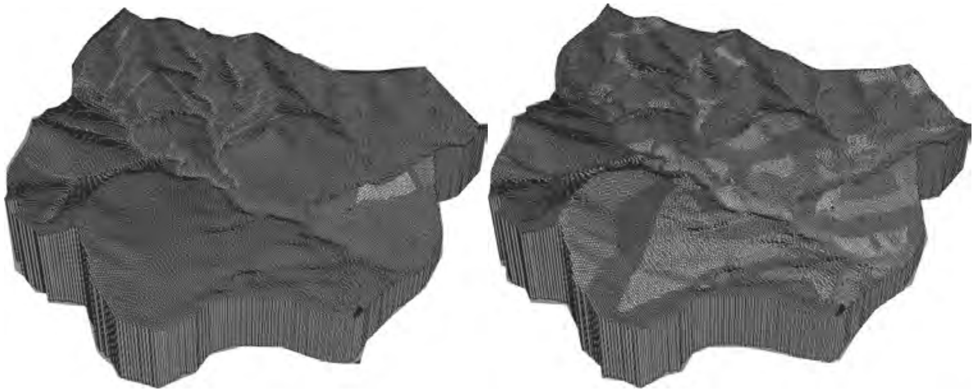

Figure 3. Runoff distribution for two events: left: a small event generating only locally runoff and to the right extremely high rainfall intensity (2.8 mm/min during 3 minutes) creating runoff at broad scales. Brighter colours indicate stronger runoff response.

REFERENCES

- De Baets, S., Poesen, J., Gyssels, G. and Knapen, A. 2006. Effects of grass roots on the erodibility of topsoils during concentrated flow. *Geomorphology* 76(1-2), 54-67.
- Bracken, L.J. and Croke, J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* 21(13), 1749-1763.
- Busch, G., Sutmoeller, J., Krueger, J.-P. and Gerold, D. 1999. Regionalization of runoff formation by aggregation of hydrological response units: a regional approach. In: B. Diekkrueger, M.J. Kirkby and U. Schroeder (Eds), *Regionalization in Hydrology*. IAHS Press, Wallingford, pp. 45-51.
- Cammeraat, L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in Southeast Spain. *Agriculture, Ecosystems & Environment* 104, 317-332.
- Dooms, T. 2003. *Using hydrological response units for modelling runoff in a first order catchment in the Guadalentin basin*, MSc thesis University of Amsterdam, Amsterdam.
- England, C.B. and Stephenson, G.R. 1970. Response units for evaluating the hydrologic performance for rangeland watersheds. *J. of Hydrology* 11, 89-97.
- Geeson, N., Brandt, C. J. & Thornes, J.B.(Eds) 2002. *Mediterranean Desertification: a Mosaic of Processes and Responses.* John Wiley.Chichester.
- Hooke, J.M., Sandercock, P.J., Marchamalo Sacristán, M, Wesemael, B. van, Meerkerk, A. Torri, D., Borselli, L., Salvador, M.P. Yanez, M.S., Castillo, V., González-Barbára, G., Navarro-Cano, Querejeta Mercader,J.I. Boix-Fayos, C., Cammeraat, L.H., Lesschen, Poesen, J., De Baets, S. 2007. *Combating Land Degradation by Minimal Intervention: The Connectivity Reduction Approach*. University of Portsmouth, Portsmouth.
- Imeson, A.C. and Cammeraat, L.H. 1999. Scaling up from field measurements to large areas using the Desertification Response Unit and Indicator Approaches. In: O. Arnalds and S. Archer (Eds), *Rangeland Desertification*. Advances in Vegetation Science 19. Kluwer Academic Publishers, Dordrecht, pp. 99-114.
- Lesschen, J.P., Schoorl, J.M. and Cammeraat, L.H. 2009. Modelling runoff and erosion for a semi-arid catchment based on hydrological connectivity to integrate plot and hillslope scale influences. *Geomorphology*, in press (preview accessible)
- Thornes, J.B. (Ed) 1990. *Vegetation and erosion*. John Wiley&Sons, Chichester.
- Wesseling, C.G., Karssenberg, D., Van Deursen, W.P.A. & Burrough, P.A. 1996. Integrating dynamic environmental models in GIS: the development of a Dynamic Modelling language. Transactions in GIS 1, 40-48.