Distributed hydrological modelling within SCARCE project: integrating water, sediments, quality and vegetation.

Félix Francés, Chiara Medici, Gianbattista Bussi, Alicia García, M. Barrios and M. Pasquato

Technical University of Valencia, Valencia, Spain

Introduction

SCARCE is a project that aims to describe and predict the relevance of **global change impacts** on water availability, water quality and ecosystem services in Mediterranean river basins of the Iberian Peninsula, as well as their impacts on the human society and economy.

To satisfy this objective, we need a **means of extrapolating** from the available measurements, in both space and time, into the future (where measurement are not available) to assess the likely impact of future changes (Beven, 2001). Mathematical models of different types provide a means of **quantitative extrapolation** or **prediction** that will hopefully be helpful in decision-making.

Water related models are mathematical models used to reproduce several descriptors (called also state variables) of the **Water Cycle** within a catchment. Indeed, the water balance is the driving force behind everything that happens in the catchment. Hence, to accurately predict the movement of pesticides, sediments or nutrients, the hydrological cycle simulated by models must conform to what is happening in the catchment.

To this end, TETIS is a distributed rainfall-runoff conceptual model (Francés et al. 2002 and 2007; Vélez et al. 2007 and 2009) developed by our research group during the last fifteen years. The TETIS model has been tested in different watersheds and under a variety of climatic conditions for a wide range of spatial and time scales, providing satisfactory results.

Within the SCARCE project, a new and comprehensive version of the TETIS model is being developed. The **TETIS-SCARCE** model will include new modelling capacities like: sediment production, transport and deposition; interactions between vegetation and soil moisture in semiarid climates; N and P catchment cycles; integration of riparian ecosystems into hydrological models. The new model will upscale these processes form mesoscale to water body and catchment scales.

Sediment cycle

Sediment cycle modelling is one of the most problematic aspects in environmental modelling and watershed managing. A sediment yield model might be a useful tool for determining soil redistribution subject to environmental changes, especially in zones characterized by long dry periods followed by heavy burst of erosive rainfall.

Moreover, a distributed approach to erosion and sediment yield modelling (like the one provided by the TETIS-SCARCE model) can lead to improvements for the solution of several sedimentological and geomorphological problems, such as sediment redistribution, location of heavy erosion and soil deposition zones, estimation of soil erosion and sediment yield at different spatial scales and assessment of land use change effects on the sediment cycle.

The sediment sub-model already coupled to the TETIS model, with the purpose of representing erosion and sediment transport at the basin scale, is based on the CASC2D-SED (Rojas, 2002) erosion submodel (Bussi et al, 2009). Moreover, more recently an automatic calibration algorithm has been implemented. Sediment production, transport and deposition are controlled by two characteristics: the sediment availability and the flow transport capacity. Fine sediment transport is limited by sediment availability in the watershed, while the transport of coarse material is limited by flow transport capacity (Julien, 1995).

Vegetation dynamics

The **vegetation** indeed plays an important role within the water cycle, particularly in arid and semiarid climates, where it shows adaptation strategies to survive at low soil water content. The soil water content depends upon the atmosphere, the soil characteristic and the vegetation. However, it is the vegetation that controls to great extent the water fluxes and therefore the feedback mechanisms between soil and atmosphere. Hence, from the modelling point of view, the vegetation leaf biomass must be a state variable instead of a fixed parameter. For this reason, a conceptual dynamic (slope and riparian) vegetation sub-model (Quevedo and Frances, 2008) is being coupled with the TETIS model. The state variable related to the vegetation is the relative leaf biomass, which is equivalent to the crop coefficient factor used traditionally for the evaluation of the actual evapotranspiration (Allen et al., 1998), but not fixed in time. The aim is to represents the vegetation response to soil moisture fluctuations and the influence of the actual leaf biomass on soil water availability and evapotranspiration.

The **riparian zone vegetation** represents a key element in sediment retention processes, acting as a physical barrier as well as increasing roughness, hence reducing the water velocity. Moreover, the vegetation located in the river margins has also been shown to be a key element in controlling low flows and water quality (Bernal et al., 2005 and Medici et al., 2010). The riparian zone vegetation type, density and coverage exerts a great influence also on the fauna habitat and its distribution along the river due, for example, to its shadow-effect which can produce temperature variations or to the organic matter that may fall and accumulate on the streambed. As far, we focused our research efforts on modelling the riparian vegetation distribution by means of evapotranspiration index calculation. Namely, the RibAV model (Morales and Francés, 2009) has been used in order to obtain the most probable vegetation functional type in each selected simulation point, through the highest Evapotranspiration Index. Most recently, new aspects as the shear stress on the vegetation, flood duration and recruitment zones distribution have been included into the model.

Water quality

Nitrogen (N) and **Phosphorus (P)** are present in both terrestrial and aquatic ecosystems and their importance in controlling plant growth and freshwater trophic status is well recognized (Wade et al., 2001, Vitousek et al. 2009; Chu et al. 2008; Schlesinger et al 2006; Ocampo et al. 2006).

An N-submodel to represent the inorganic nitrogen cycle in a catchment has been already developed, based on the INCA-N model (Whitehead et al., 1998??; Wade et al., 2002). The N-submodel adopted provides a simplified conceptualization of the soil nitrogen cycle considering mineralization, nitrification, immobilization, denitrification, plant uptake, and ammonium adsorption/desorption. It also includes nitrification and denitrification in the shallow perched aquifer. In particular the model has been thought for Mediterranean ecosystems, which are subjected to alternate dry and humid conditions that influence the soil microbial activity. Hence, additional mechanisms to take into account this aspect were included. Namely, these new elements are: biological thresholds responses to soil moisture in order to reproduce the pulse dynamic observed in such environment; a specific function for the soil moisture correction factor for the mineralization process, and finally nitrification and denitrification processes associated to the shallow perched water table and finally (Medici et al., 2010).

The future work about nutrient modelling will be focused on P export from source areas within a catchment and its routing to the stream.

Scaling

It is worth to highlight that the process-oriented model TETIS-SCARCE is distributed in space to cope with the natural spatial variability of the water cycle and associated processes within the catchment. However, in spite of all the attempts that have been made in the past, it is still difficult to establish an optimum modelling spatial discretization providing the best performance of a distributed hydrological model. In fact, if low spatial resolution is adopted, the spatial variability effect may be lost and errors may occur due to omitting relevant information. On the other hand, if high spatial resolution is used, the possibility of error may increase, since parameter identifiability is reduced and there is generally limited data availability (Shrestha et al., 2006 and 2007; Didszun and Uhlenbrook, 2008). To face this issue, the spatial aggregation of the TETIS model effective parameters (as far, only static storage capacity parameter Hu and effective saturated hydraulic conductivity parameter ks) is being analyzed as well as its implications for the definition of a critical cell size. Moreover, also the importance of soil parameters sub-grid heterogeneities representation is being tested in terms of model performance improvement (Barrios et al. 2010).

Synergies and conclusion

It is worth to highlight that all the **ecological processes** mentioned and the **hydrological processes** can **interact strongly** in landscapes, yet these processes are often studied separately. On one hand, the implication of the water cycle over each ecological process considered has already been highlighted. On the other hand, soil erosion not only results in off-site sediment movement that can cause problems downstream, increasing potential for flooding, but sediments can carry nutrients and pesticides that degrade water quality, which is becoming more of a concern in the world (Zheng Fen-Li, 2005). It is also well known the trapping/retention-effect that vegetation may exert on runoff and sediment transport. Finally, nutrients availability is indeed a key factor for plant growth. Ecohydrological interactions can have profound effects and management implications at larger watershed and catchment scales, not just at local vegetation patch–interpatch and hillslope scales.

According to this idea, the TETIS-SCARCE model will try to simultaneously take advantage of the knowledge provided by different type of data and observed state variables, in order to better constrain model parameters and obtain more robust estimations.

In fact, in an earlier work by Medici (2010) about the general sensitivity analysis of an N-model applied in a small Mediterranean forested catchment, it was suggested that stream nitrate and ammonium concentrations may help to constrain rainfall-runoff parameters values and to reject some hydrological mechanisms in favour of others. It was obtained that when hydrology and water quality were modelled simultaneously the number of equally good parameter sets decreased dramatically. Hence, a simultaneous calibration strategy of both rainfall-runoff model and N-submodel was the best solution, which is in agreement with what found also by McIntyre (2005).

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration (guidelines for computing crop water requirements), FAO Irrigation and Drainage Paper, No. 56, 326 pp., 1998.

Barrios, M. and Francés, F. (2010). Spatial scale effect on the upper soil effective parameters of a distributed hydrological model. *Hydrological processes*. Accepted.

Bernal S., Sabater F., Butturini A., Nin E., Sabater S.: Factors limiting denitrification in a Mediterranean riparian forest. Soil Biol. Biochem., 39, 2685-2688, 2007.

Beven K. 2000. Rainfall-Runoff Modelling. The Primer. John Wiley & Sons, LDT.

Bussi, G.B.,. Montoya J.J y Francés F., 2009. Calibración de un modelo conceptual distribuido del ciclo de sedimentos. Aplicación a la cuenca experimental de Goodwin Creek (EEUU). Oral presentation. Congreso: Primeras Jornadas de Ingeniería del Agua, Madrid, octubre 2009, 11 pp, ISBN-CD: 978-90-78046-09-7. Resumen en pp 81-82, ISBN: 978-90-78046-10-3

Didszun, J., Uhlenbrook, S. 2008. Scaling of dominant runoff generation processes: nested catchment approach using multiple tracers. *Water Resources Research* **44**. DOI: 10.1029/2006WR005242.

Francés, F., Vélez, J.I., Vélez, J.J. 2007. Split-parameter structure for the automatic calibration of distributed hydrological models. *Journal of Hydrology* **332**: 226-240. DOI: 10.1016/j.jhydrol.2006.06.032.

Francés, F., Vélez, J.J., Vélez, J.I., Puricelli, M. 2002. Distributed modelling of large basins for a real time flood forecasting system in Spain. In Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, USA; CD Format.

Julien, P. Y. 1995. Erosion and sedimentation. Cambridge University Press.

McIntyre N., Jackson B., Wade A.J., Butterfield D., Wheater H.S., 2005. Sensitivity analysis of a catchment-scale nitrogen model. J. Hydrol., 315, 71-92.

Medici C., Bernal S., Butturini A., Sabater F., Martin M., Wade A.J., Francés F., 2010. Modelling the inorganic nitrogen behaviour in a small Mediterranean forested catchment, Fuirosos (Catalonia), Hydrol. Earth Syst. Sc., 14, 1-15.

Medici, C. 2010. Progressive development of a hydrologic and inorganic nitrogen conceptual model to improve the understanding of small Mediterranean catchments behaviour. PhD Tesis. Universidad Politécnica de Valencia.

Morales- de la Cruz, M. & Francés, F., 2009. Vegetation and water use modelling in a semi-arid riparian zone in Guatemala, by coupling basin and river reach hydrological processes. Proceed. Internat. Conf. Sci. Inf. Tech. Sust. Manag. Aq. Ecosyst. Concepcion, Chile., ISE-1B2-PH1 (conf187a223), 93.

Quevedo, D. and Francés F. 2008. A conceptual dynamic vegetation-soil model for arid and semiarid zones. Hydrology and Earth System Sciences 12: 1175-1187.

Rojas, R. 2002. GIS-based upland erosion modeling, geovisualization and grid size effects on erosion simulations with CASC2D-SED. Ph. D. dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Schlesinger W.H., Reckhow K.H., Bernhardt E.S.: Global Change: The nitrogen cycle and rivers. Water Resour. Res., Vol. 42, W03S06, 2006.

Vélez, J.J., Francés, F., López, F. 2007. Calibration strategy for hydrological distributed conceptual models. In Earth: Our Changing Planet. Proceedings of IUGG XXIV General Assembly, Perugia, Italy; 4675.

Vélez, J.J., Puricelli, M., López Unzu, F., Francés, F. 2009. Parameter extrapolation to ungauged basins with a hydrological distributed model in a regional framework. *Hydrology and Earth System Sciences* **13**: 229-246.

Vitousek P.M., Naylor R., Crews T., David M.B., Drinkwater L.E., Holland E., Johnes P.J., Katzenberger J., Martinelli L.A., Matson P.A., Nziguheba G., Ojima D., Palm C.A., Robertson G. P., Sanchez P.A., Townsend A.R., Zhang F.S.: Nutrient imbalances in Agricultural Development. Science, Vol. 324, no. 5937, pp. 1519-1520, 2009.

Wade A. J., Durand P., Beaujouan V, Wessel W. W., Raat K. J, Whitehead P. G, Butterfield D., Rankinen K., Lepisto A.: A nitrogen model for European catchments: INCA, new model structure and equations. Hydrol. Earth Syst. Sc., 6(3), 559-582, 2002. (See also Errata. Hydrol. Earth Syst. Sci., 8, 858-859.).

Wade A.J., Hornberger G.M., Whitehead P.G., Jarvie H.P. Flynn N., 2001. On modelling the mechanisms that control in-stream phosphourus, macrophyte, and epiphyte dynamics: An assessment of a new model using general sensitivity anlaysis. Water Resour Res; 37(11), 2777-2792, Paper number 2000WR000115.

Whitehead P. G., Wilson, P.G. and Butterfiled, D.: A semi-distributed Nitrogen Model for Multiple Source Assessments in Catchments (INCA): Part 1 – Model structure and Process Equations. Sci. Total Environ., 201/211, 547-558, 1998.

Zheng Fen-Li, 2005. Effects of Accelerated Soil Erosion on Soil Nutrient Loss after Deforestation on the Loess Plateau. Pedospkere 15(6): 707-715. ISSN 1002-0160/CN 32-1315/P