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Mapping headwater systems using a HS-GIS model. An application to landscape structure and land use planning in Portugal

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ABSTRACT

The Headwater System (HS) is defined as the area between the ridge line, and the beginning of the channel network. The HS have high importance in the hydrological, geomorphological, and biological processes of the drainage basin. It is crucial to map HS areas in order to define the suitable land uses in the landscape related policies.

The identification of the channel network beginning is particularly difficult as well as its mapping at a landscape scale. The field identification is costly in time and labor, being more operative to use models and mathematical thresholds to identify the drainage area thresholds that defines the beginning of the channel network. The aim of this work was to contribute to headwaters system mapping with the construction of a Geographic Information System model, using as channel network beginning, the thresholds of 0.1 km^2 drainage area. This threshold was compared and validated with 92 channel heads occurring in Portugal. The model was created in GIS allowing to define the headwater system, in order to be included in landscape plans and in green infrastructure delimitation. It was applied in Portugal and compared with data from National Ecological Reserve (REN) in Alentejo Region. It was concluded that the proposed model is a useful tool to define headwater systems with precise criteria, bridging the gaps of the existent mapping policies from REN policy. The current evaluation of land use and land cover in the HS from Portugal showed a high percentage of eucalyptus and maritime pine, which are not the best land use for these areas.

1. Introduction

The river basin is both a geomorphological and a land use planning unit (Tricart, 1972; Directive 2000/60/EC). Its hydrology is in close relation with land use management and policy (Haigh and Křeček, 1991). Headwaters are components of the river basin and among the least studied areas, receiving little attention in planning (Benda et al., 2005). They are commonly defined as first order streams (Stanfield and Jackson, 2011; Freeman et al., 2007; Russell, 2008), or as those streams without tributaries, according to Strahler's definition (Strahler, 1952). Some also define them as zero-order basins (Tsukamoto et al., 1982). In this work, headwaters are evaluated as more complex systems than the first order streams, which encompass the whole area between the ridge line and the beginning of the channel network – the Headwater System (HS). The HS has two major types: steep slopes near the drainage divide (rugged relief) or gentle slopes near the drainage divide (smooth relief) (Magalhães et al., 2012).

The most widely recognised role of HS is its importance in river basin dynamics, namely, the upstream-downstream interactions that affect water management (flood prevention) and ecosystem protection (Gomi et al., 2002; Benda et al., 2005; Freeman et al., 2007). Because of special biophysical characteristics such as altitude, precipitation, and soil, the HS often gives rise to unique habitats (Gomi et al., 2002; Haigh et al., 2004; Benda et al., 2005; Freeman et al., 2007; Jaeger et al., 2007; Henkle et al., 2011). Interactions between the upstream and downstream systems also affect organic matter dynamics (Karlsson et al., 2005). Linkages between HS, affect the circulation of some species, like aquatic-riparian biota (Olson and Burnett, 2009). Another important role of HS is the rainwater infiltration and ground water recharge, which much influences water quality and quantity (Haigh et al., 2004).

Despite the knowledge about the high importance of HS in the hydrological, geomorphological, and biological processes of the river basin, there has not yet been established a precise methodology to map these areas to be included in Land Use Plans. Thus, the main goal of this work is to contribute to HS mapping, at the landscape scale, with the construction of a Geographic Information System (GIS) model, using an accurate threshold. Another objective is to evaluate for Portugal the

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current land use in the mapped HS and to contribute to the clarification of the best land use. To model HS using GIS and achieve these objectives, it was assumed that channel networks initiate at 0.1 km^2 of the drainage area. This approach was explored and validated by photo-interpretation of aerial photographs from Portugal.

Below, the main difficulties regarding headwaters mapping are pointed out appropriate. Further, land uses for HS are proposed in the context of current land use policies. These fulfill the purposes of ensuring natural resources protection, guaranteeing the ecological equilibrium of landscape and minimizing hazards.

1.1. The land use in headwaters and the land use policy context

The land use in HS will be a key element to the functionality of the river basin. The existence of deep soils or forest cover diminishes soil erosion and flooding risks (Epp, 1990; Molchanov, 1971). The HS can be critical in forest planning to avoid rural fires if covered with native flora, or native flora intercalated with open spaces (agriculture or pastures) (Magalhães et al., 2012). Paracchini et al. (2000) also noticed that the conservation of headwaters is related to forest management. In addition, Jaeger et al. (2007) suggests that timber harvest near headwaters can have negative consequences in water and sediment regimes and should be restricted. A proper land use plan of the river basin, considers the knowledge of the ecological processes of the landscape (Comino et al., 2016), which will provide a slow reaction of the landscape system, promoting the dynamic geomorphological equilibrium (Pena et al., 2010; Pena and Abreu, 2012).

Since Water Frame Directive (WFD) (Directive 2000/60/EC), the awareness in river basin planning and management, has been rising. However, the main focus for implementation is water quality, while the importance of headwater protection has been neglected (Lassaletta et al., 2010). In Portugal, the WFD was transposed into the National Water Law in 2005 (Law n.° 58/2005). However, land use planning for water resources protection focuses mainly on the banks of lakes and reservoirs of public waters and the coastal and estuarine borders. The integrative approach to managing and planning the river basin, with the inclusion of HS, is largely forgotten.

The National Land Use Program for Portugal is a strategic framework (Law n.° 58/2007) that identifies 24 major land use problems and different priorities for actions that should be implemented. From those problems, two are directly related to river basin management: (1) natural resources and risk management; and (2) degradation of water quality and poor management of water resources. However, in the definition of the priority actions, the solutions focus on the monitoring of water ecological and chemical status (cf National Water Law n.° 58/2005) without referring to the need for the protection of the upland areas of the river basin.

Currently, the Portuguese National legal framework does not embrace the importance of HS in the river basin healthy functioning. However, at the beginning of the 80′s of the twenty century the headwaters became part of the National Ecological Reserve (REN) legal framework. It is mandatory for land use plans to map REN areas, which are defined as biophysical structures essential to the ecological stability and the rational use of natural resources. Currently, REN are only mapped at municipal scale, being absent in the regional and national spatial planning plans. National Ecological Reserve recognizes headwaters, which are defined as the areas between the ridgeline and the beginning of the river system (Decree-Law n° 321/83). However, in the 1990s, the concept was reformulated as the “concave areas of upstream watershed”. The absence of objective mapping criteria has led to different mapping methodologies in local administrative boundaries. More recently, headwater mapping was dropped from the REN guidelines (RCM n° 81/2012), and HS are no longer mapped. The authors regard this as a retreat in land use planning in Portugal.

Despite the limitations in the current legal framework, recently an important tool in planning – the green infrastructure – was linked to ecosystem restoration, biodiversity promotion (EC, 2011), and natural water retention measures in the watershed (EC, 2012), providing an opportunity to include the HS as a component of the green infrastructure map.

1.2. Headwaters mapping criteria and difficulties

Despite the lack of attention given to the planning of the headwaters, they have been considered increasingly as a top priority area in environmental management (Haigh et al., 2004). However, the headwaters concept has different interpretations and is hard to map although the different approaches share the identification of the channel network initiation. It is particularly difficult to map the channel heads at a landscape scale since this depends on geology/lithology (Jaeger et al., 2007) and soil properties. Moreover, with the development of the Geographic Information System (GIS), identification also depends on the digital terrain model scale and accuracy (Gomi et al., 2002; Colson et al., 2008). Despite the challenges, the mapping of HS areas at the landscape scale is needed to provide sustainable land use plans for decision-makers.

The field identification of channel network initiation is costly in time and labor. Hence, it is more practical to use models and mathematical thresholds. To map channel network initiation accurately, it is necessary to identify which thresholds should be used. Former studies related the channel head to the rill development (Montgomery and Foufoula-Georgiou, 1994). Accordingly, channel heads are associated with changes in the dominant sediment transport process, which can be measured as the critical contributing area to start channel heads (Vogt et al., 2003, 2007). This is consistent with the findings of previous researchers that related the “belt of no erosion” (Horton, 1945) or “zone of no erosion” (Garner, 1974) to the area between the drainage divide and the beginning of the drainage network, although surface wash is always possible in these areas (Huggett, 2003). Montgomery and Foufoula-Georgiou (1994) concluded that 0.1 km^2 was the minimum drainage area, required to initiate a channel, while Gomi et al. (2002) defined headwater areas as having drainage areas smaller than 1 km^2, and the HS network as one with more than 1 km^2 of drainage area. Further studies, with field work and statistics, concluded that most channel heads in HS were fed by drainage areas of between 0.01 km^2 and 0.1 km^2 (Henkle et al., 2011).

2. Case study

The case study is located in Continental Portugal between 36° 57′ and 42° 9′ North and 6° 11′ and 9° 30′ West and focuses on the Alentejo region in the South of Portugal (Fig. 1). The Alentejo was chosen due to its gently wavy relief, where it is difficult to define headwaters. When the terrain morphology is more rugged, the different zones of the river basin are more clearly marked. The Alentejo region was also selected in order to compare the results of the HS model with the data from the gathered municipal land use plans. This comparison can provide an evaluation of the mapping consistency between national, regional, and municipal scales.

There are a great variety of landforms in Portugal, ranging from hilly mountains to open landscapes with wavy relief, as is the case of Alentejo Region, and large alluvial valleys. The diversity of landforms is a consequence of the variety of the geological and lithological units in Portugal ranging from Precambrian and Paleozoic formations (granites, shists and graywakes, and metamorphic rocks) to Cenozoic (carbonates, marls, sandstones, gravels, sands, mud, and silt) (Ribeiro et al., 1979).

3. Methods

In this work, the HS was defined, as the area between the ridgeline and the beginning of the channel network. Based on this conceptual model (Fig. 2) a GIS model was created to map the headwaters (Section