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Delineation of the riparian zone in data-scarce regions using fuzzy membership functions: An evaluation based on the case of the Naryn River in Kyrgyzstan

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ABSTRACT

Riparian zones contain important ecosystems with a high biodiversity and relevant ecosystem services. From a process point of view, riparian zones are characterized by the interaction of hydrological, geomorphological and ecological processes. Consequently, their boundary is dynamic and blurred as it depends on not only the local valley morphology but also the hydrological regime. This makes a delineation of riparian zones from digital elevation data a challenging task as it should represent this blurred nature of riparian zone boundaries. While the application of high resolution topography from LIDAR and hydraulic models have become standard in many developed countries, studies and applications in remote areas still commonly rely on the freely available coarse resolution digital elevation models. In this article, we present the delineation of riparian zones from the SRTM-1 elevation model and fuzzy membership functions for the Naryn River in Kyrgyzstan having a length of approximately 700 km. We evaluate the extraction of the underlying channel network as well as the different indicator variables. The maximum user's accuracy for the delineation of riparian zones along the entire Naryn River is 82.14% reflecting the uncertainty arising from the heterogeneity of the riverscape as well as from the quality of the underlying elevation data. Despite the uncertainty, the fuzzy membership approach is considered as an appropriate method for riparian zone delineation as it reflects their dynamic, transitional character and can be used as indicator of connectivity within a riverscape.

1. Introduction

Riparian zones are important features of the landscape as these ecotones are hotspots of biodiversity and have manifold ecological functions (Tabacchi et al., 1998; Naiman et al., 2005). Furthermore, they offer also relevant ecosystem services (Postel and Carpenter, 1997; Arthington et al., 2010). In the semi-arid climate of Central Asia, the riparian zones along the inland rivers have an even higher importance as the runoff in the rivers generated from snow and glacier melt in the mountains is the most important water resource (Karthe et al., 2015). There are several definitions of "riparian zone". The criteria range from vegetation to fauna and soils to hydrology (Naiman et al., 2005). In a natural state, riparian zones are seen as transitional areas between the aquatic and the terrestrial environment (Ward et al., 2002; Verry et al., 2004; Naiman et al., 2005). In a broad sense, they can be seen as the zones influenced by the hydrological and geomorphological processes in the river channel including the channel itself with its instream features as well as the adjacent floodplain (Nanson and Croke, 1992; Hupp and Osterkamp, 1996; Gurnell et al., 2016). However, the connectivity to the channel is not consistent across space and time, making it difficult to judge whether an area is still connected to the river channel under the contemporary hydrological regime (Croke et al., 2016). While in one year higher floodplain areas might be fully connected to the river channel, they might be disconnected for the next decades. On the contrary, low elevation zones might be connected more frequently. As a consequence of these dynamics, riparian zones are bordered by a blurred transition zone rather than a sharp boundary (Gurnell et al., 2016).

A comprehensive investigation as well as management require objective and spatially continuous information about the extent of the riparian zone. Thus, many attempts have been made for its delineation. Early approaches used for instance the vertical distance above channel network as an indicator (Williams et al., 2000) or established indices based on the local topography (Gallant and Dowling, 2003; Manfreda et al., 2008). Furthermore, relationships of the floodplain width with the catchment area have been made (Nardi et al., 2006). A more recent, elevation data based approach was proposed by Alber and Piégay (2011) who presented an analysis of river networks using a spatial disaggregation/aggregation method of various riverscape parameters, among them also the floodplain width. This approach has also been implemented in form of an ArcGIS toolbox (Roux et al., 2015). On the pan-European scale, the delineation of floodplains has been demonstrated using elevation data, multispectral satellite imagery and various existing datasets (Clerici et al., 2011, 2013; Weissteiner et al., 2016).

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Also machine learning has already been applied for modeling the riparian zone extent using different morphological indicators (Salo and Theobald, 2016). All of these frameworks, however, cannot fully represent the dynamic character of the fuzzy boundary of the riparian zone as they rely on static thresholds of indicators derived from a digital elevation model (DEM) (Fernández et al., 2012; Roux et al., 2015; Salo and Theobald, 2016). This is in accordance with Burrough (1992) who noted that the crisp GIS data structures like polygons or binary rasters fail at representing "worlds consisting of complex continua" (Burrough, 1992, p. 396). The availability of high resolution topography and hydraulic models helps solving this issue and makes process-oriented information about the riparian zones more widely available (Newson and Large, 2006; Michez et al., 2017).

Beside this technological progress, research in remote areas or low budget applications still commonly rely on the global, open access elevation models like from the Shuttle Radar Topography Mission (SRTM) and from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM) (Schmitt et al., 2014; Jarihani et al., 2015). Using this kind of datasets for hydromorphological modeling is associated with challenges. Metz et al. (2011) for instance demonstrated the uncertainty related to channel extraction. On the other hand, Clerici et al. (2013) presented the delineation of a pan-European floodplain network using the ASTER GDEM and remote sensing. They found that the use of fuzzy logic resulted in good accuracies despite the coarse resolution of the underlying data (Clerici et al., 2013; Weissteiner et al., 2016). However, their approach relies on further auxiliary databases like e.g. flood maps or the Corine landcover product. Such datasets are not available for most developing countries. Thus, there is a need for a delineation approach based on digital elevation data only.

In this study, we take the Naryn River in Kyrgyzstan as an example and discuss the use of fuzzy membership functions for representing the riparian zone in an ecologically meaningful, process oriented way but without data intensive hydraulic models. Furthermore, we evaluate the performance of the SRTM elevation data for channel network extraction and the fuzzy delineation of the riparian zone. To achieve these goals, we test two approaches for channel extraction as well as different indicators for a fuzzy computation of the riparian zone. Our approach requires only a minimum of field data and is based on freely available elevation data and open source software. Therefore, this study not only improves the information about the riverscape of the Naryn River but also provides a useful method for river research in other data-scarce regions.

2. Study area

The study area is the Naryn Catchment in Kyrgyzstan with a focus on the part upstream from the Toktogul Reservoir (Fig. 1).

This catchment has an area of 52,130 km^2 and its elevation ranges from 868 m at the Toktogul to 5133 m in the Tian Shan mountains (values derived from the SRTM-1 elevation model). Upstream from the Toktogul Reservoir, the Naryn River is in a natural state on a flow length of >700 km. The absence of dams and embankments guarantees full longitudinal and lateral connectivity of the river. The Naryn shows a diverse morphology with steep, confined headwaters, a braided section in the central part of the catchment and a >150 km long gorge leading to the Toktogul Reservoir. Riparian areas are mainly located along the braided reaches (Betz et al., 2016). Average annual discharge at the gauge in Naryn City is 92.12 m^3 s^{-1} but increases to 323.33 m^3 s^{-1} at the inflow to the Toktogul. The climate is highly continental with cold winters and hot summers. An incision of the river leads to the formation of river terraces. The active floodplain within the riparian zone is ultimately bounded by these terraces. The riparian zone is also structured into a floodplain and a braided plain with the river channel and gravel bars covered by pioneer vegetation. Dominating species of the floodplain ecosystems are *Populus nigra* and different species of *Salix* like *Salix talassica*. Further frequently occurring plants include *Tamarix* spp. and *Hippophae rhamnoides*. A photograph of the riparian ecotone forming under these conditions is shown in Fig. 2.

3. Data and methods

We use the SRTM-1 elevation model at a resolution of 1 arc sec or a pixel size of 24 × 24 m when projected to UTM. This digital elevation model (DEM) is available under the public domain from the United States Geological Survey. Further specifications about this dataset can be found in Farr et al. (2007). All analysis except the sink filling and channel extraction from the hydrologically corrected DEM have been conducted with a combination of R (R Core Team, 2015) and GRASS GIS (Neteler et al., 2012). An R script is available as supplementary material.

3.1. Channel network derivation and quality assessment

Basis for most riparian zone indicators is a channel network which needs to be derived from a flow accumulation grid computed based

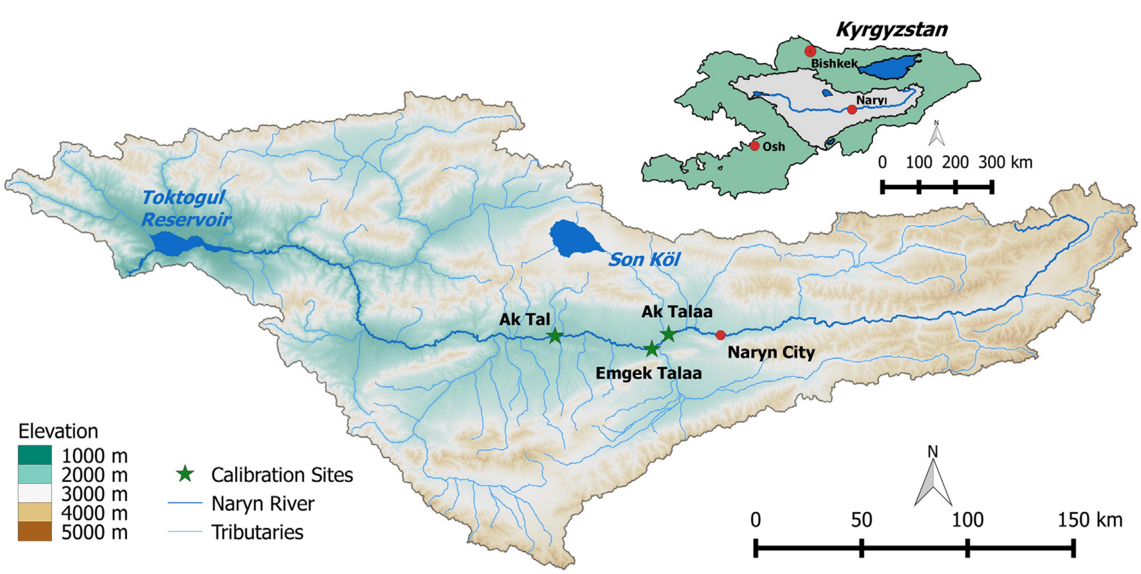

Fig. 1. Location of the Naryn catchment within Kyrgyzstan and overview of the study area; The green stars indicate the location of the sites used for the field calibration of the fuzzy logic models.