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Complex land cover change, water and sediment yield in a degraded Andean environment

Armando Molina [a,*], Veerle Vanacker [b], Vincent Balthazar [b], Diego Mora [c], Gerard Govers [a]

[a] Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, B-3001 Heverlee, Belgium

[b] Earth and Life Institute, Georges Lemaitre Centre for Earth and Climate Research, University of Louvain, 3 Place Louis Pasteur, B-1348 Louvain-la-Neuve, Belgium

[c] Programa para el Manejo del Agua y del Suelo (PROMAS), Universidad de Cuenca, Av. 12 de abril s/n, Cuenca, Ecuador

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SUMMARY

Rapid land use/-cover change has increasingly transformed the hydrological functioning of tropical Andean ecosystems. The hydrological response to forest cover change strongly depends on the initial state of the ecosystem. Relatively little is known about human-disturbed ecosystems where forest plantations have been established on highly degraded land. In this paper, we analyze the impact of forest change on water and sediment fluxes for a highly degraded Andean catchment. Different pathways of land cover change (1963–2007) are observed in the Jadan catchment, with deforestation taking place in remote uplands and recovery and reforestation in the middle and lower parts where agricultural and bare lands are prevalent. Time series analyses of streamflow and rainfall data (1979/1982–2005/2007) show significant shifts in the distribution of rainfall and flow data. Changes in discharge are not resulting from changes in precipitation, as the direction of change is opposite. The removal of native forest for rangeland or croplands (by $-20\ \mathrm{km}^2$) is likely to have contributed to the increase in total annual water yield, through an increase in annual baseflow by 25 mm. The observed changes in peakflow are important as the 1st percentile highest flow rates were 54% lower, while the 1st percentile rainfall amounts increased by 52%. The observed decrease in peakflow cannot be explained by clearcut of native forest, but is likely to be related to reforestation of degraded lands as well as spontaneous recovery of vegetation on remaining grazing lands. Over the same time period, a major decrease in specific sediment yields and suspended sediment loads was observed. Although deforestation in the upper parts led to increased landslide activity, this change is not reflected in an increased sediment yield. Small upland rivers are often nearly completely blocked by landslide material, thereby reducing their potential to transport sediment. In contrast, the reduction in estimated erosion is likely to be caused by the reduction of the degraded areas in areal extent as well as to the (partial) recovery of the vegetation in these areas.

1. Introduction

The Andean headwater basins function as important regulators of the water and nutrient supply to the downstream reaches of the Amazon River. Interactions between human activities (e.g. infrastructure, agriculture and land use change) and the physical environment have increasingly transformed the hydrological functioning of Andean ecosystems (Vanacker et al., 2003a; Podwojewski et al., 2002). In these human-modified landscapes, land use/-cover change may have a profound effect on riverine water and sediment fluxes (Harden, 2006; Vanacker and Govers, 2007a; Little et al., 2009). The hydrological impacts of land use/-cover change are diverse, as changes in vegetation affect the various components of the hydrological cycle including evapotranspiration, infiltration and surface runoff (Costa et al., 2003; Bruijnzeel, 2004).

The effect of forest cover on water yields has been demonstrated for small (mostly experimental) catchments where the natural vegetation was removed and/or replaced by plantation forests (Buytaert et al., 2006; Bosch and Hewlett, 1982; Bruijnzeel, 1990, 2004). Previous studies have shown an increase in streamflow after massive removal of tall vegetation on the catchment slopes, and a decrease in streamflow after afforestation. Ruprecht and Schofield (1989) showed that the conversion of native forest into agricultural land increased streamflow as result of decreased transpiration and interception. Exotic tree plantations on natural grasslands (such as afforestation with *Eucalyptus gl.* in Sikka et al. (2003)), or conversions from native forest to exotic plantations (such as *Pinus radiata* in Little et al. (2009)) were reported to have severe impacts on water yields with strong reduction of low flows and summer runoff. However, Scott and Prinsloo (2008) suggested that the

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[*] Corresponding author. Tel.: +32 16 326405; fax: +32 16 322980.
E-mail address: Armando.MolinaVerdugo@ees.kuleuven.be (A. Molina).

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longer-term effects of exotic plantations on water yield are not necessarily as harmful as predicted from shorter-term studies. Their data show that the streamflow can be reversed to pre-afforestation levels when the plantations reach maturity.

Various authors suggested that the impact of forest cover change strongly depends on the initial state of the ecosystem (Scott et al., 2005; Chazdon, 2008; Hofstede, 2011). For the paramo ecosystem (high altitudinal grasslands), there exists detailed information from short-term experimental studies on the impact of forest plantations on the hydrological response. Buytaert et al. (2006, 2007) suggested that *Pinus patula* afforestation reduced the water yield by about 50% (or an average of 242 mm y^{-1}) based on (1–3 years) of hydrological data from four experimental catchments. Farley et al. (2004) showed that conversion of natural grasslands to Pinus plantation on volcanic soils significantly reduced the water retention capacity of Andosols. In contrast, relatively little is known about disturbed ecosystems where forest plantations have been established on highly degraded land (Wilk et al., 2001; Bruijnzeel, 2004).

Some field-based information exists from plot and controlled flow experiments in reforested gully systems. Rainfall-runoff experiments at experimental plots (ranging from a few cm^2 to 1 m^2) in the tropical Andes showed that land use strongly controls hydrological processes, with significantly higher cumulative runoff coefficients on abandoned and fallow land compared to recently plowed cultivated fields (Harden, 1996; and confirmed by Molina et al. (2007)). When controlling for land use type, the surface vegetation cover determines runoff generation, and a sharp exponential decrease of overland flow generation was observed after revegetation of abandoned and fallow land (Molina et al., 2007). Garcia-Ruiz et al. (2005) showed that the hydrologic response of a highly degraded experimental catchment (284 ha) in the Central Spanish Pyrenees is highly variable, due to the existence of different runoff-generating areas (related to different land cover types and covers). Particularly, the reforestation of gully areas can have major impacts on the hydrological connectivity of degraded catchments. Controlled flow experiments in steep gully channels in the tropical Andes showed that the transfer of overland flow and sediment from the slopes towards the river system highly decreases with the presence of vegetation in the gully channels (Molina et al., 2009b).

While these data provided valuable information on how revegetation may affect water fluxes, they are insufficient to predict the hydrological and sediment response at larger scales. An important reason for this is that changes in forest cover over large areas are often not unidirectional. A prime example of the complexity of change can be seen in many areas in the Andes, where there was a clear loss of native forest vegetation at high altitudes over the last decades while at the same time arable land and grazing land at low altitudes was gradually replaced by plantations of exotic species (Wunder, 1996; Hofstede et al., 2002). Similar complex changes were observed in many areas in the world (for a comprehensive overview, see Rudel et al., 2005). Secondly, the relative importance of processes in a catchment changes with scale, depending on how various land cover units are positioned and interconnected (Cerdan et al., 2004) making it difficult to predict how the entire system will respond from localized observations.

In this paper, we analyze the hydrological response to complex forest cover change for a highly degraded Andean catchment. The Jadan catchment (ca. 300 km^2) is located in the tropical Andes, and is characterized by strong changes in forest cover since the 1960s. As is the case in many Andean catchments, large areas of upland native forests were cleared for expansion of the agricultural land. However, there was not only forest loss as fast-growing forest plantations were established on areas, which were not suitable or economically not profitable for agricultural production, such as deeply intersected gullies or river valleys and badlands (Vanacker et al., 2003a). Exotic forest plantations in the area are characterized by dense and diverse understory vegetation, with presence of grassy and shrubby vegetation (see Molina et al., 2009a). In addition to these small-scale reforestation projects, the decline of grazing pressure favored natural colonization by herbs and shrubs of degraded land. Forest plantations were to some extent driven by the desire to reduce the intense soil erosion occurring in the Jadan catchment, and were promoted by extension workers. In the areas that were most affected by rill and gully erosion, UMACPA (Unidad de Manejo y Conservacion de la Cuenca del Rio Paute) directly implemented soil and water conservation schemes including plantations with exotic rapid-growing species and construction of check-dams in active gully systems (White and Maldonado, 1991). Here, we investigate if these changes in forest cover are associated with changes in the hydrological and sediment regime by combining information from previous small-scale studies with new measurements of water and sediment yield at the catchment outlet.

2. Materials and methods

2.1. Jadan catchment

The Jadan catchment is located in the Ecuadorian Andes, and encompasses a drainage area of 296 km^2 (Fig. 1). It is located in the vicinity of the city of Cuenca, which is the third largest city in Ecuador. The landscape developed on late Tertiary volcanoclastic and sedimentary rocks that are often poorly consolidated and deeply weathered (Hungerbühler et al., 2002). The slope morphology is characterized by moderate to steep slopes, with about 1/3 of the area having slopes steeper than 40%. In most of the basin, the main valley floor of the Jadan River is relatively wide and flat, and a stack of alluvial terraces are present. The region has a tropical mountain climate (Dercon et al., 1998). The average monthly air temperatures show little seasonal variation, and the bimodal rainfall regime registers between 600 and 1100 mm of annual precipitation. The first rainy season occurs from January to May, and the second one from October to December. A marked dry season is generally observed from June to September (Celleri et al., 2007). However, interannual variability is high. The maximum 24 h rainfall intensity for a 5-year return period is about 42 mm (Cochapamba-Quingeo station, 2710 m; Baculima et al., 1999).

2.2. Time series of land cover data: 1963, 1995 and 2007

A time series of land cover data was established from panchromatic aerial photographs of 1963 and 1995 (Instituto Geográfico-Militar, Ecuador) and an ASTER satellite image of 2007. The ASTER images capture information in 15 bands of the electromagnetic spectrum: four in the visible and near infrared regions (VNIR, 0.5–1.0 μm) with a spatial resolution of 15 m; six in the infrared short wave region (SWIR, 1.0–2.5 μm) with 30 m resolution, and five in the thermal infrared region (TIR, 8–12 μm) with 90 m resolution. Five land cover categories were identified: (1) grassland and shrubland, (2) bare land with very poor vegetation cover, (3) exotic forest plantation, dominated by *Eucalyptus gl.* species, (4) agricultural land consisting mainly of rangeland and cropland, and (5) native forest. The interpretation of the land cover types on the aerial photographs of 1963 and 1995 was carried out manually using a Wild (R) mirror stereoscope with four times magnification. Land cover maps were then generated in the ILWIS 3.3 software (Integrated Land and Water Information System 2005) using the orthorectified aerial photographs as the basis for accurate on-screen digitising of the land cover categories. The land cover data of