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Morphological changes of Gumara River channel over 50 years, upper Blue Nile basin, Ethiopia

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SUMMARY

In response to anthropogenic disturbances, alluvial rivers adjust their geometry. The alluvial river channels in the upper Blue Nile basin have been disturbed by human-induced factors since a longtime. This paper examines channel adjustment along a 38-km stretch of the Gumara River which drains towards Lake Tana and then to the Blue Nile. Over a 50 years period, agriculture developed rapidly in the catchment and flooding of the alluvial plain has become more frequent in recent times. The objectives of this study were to document the changes in channel planform and cross-section of the Gumara River and to investigate whether the changes could have contributed to the frequent flooding or vice versa. Two sets of aerial photographs (1957 and 1980) were scanned, and then orthorectified. Recent channel planform information was extracted from SPOT images of 2006 and Google Earth. Channel planform and bed morphology (vertical changes) were determined for these nearly 50 years period. The vertical changes were determined based on aggradation along a permanent structure, historic information on river cross-sections at a hydrological gauging station, and field observations. The results indicate that the lower reach of Gumara near its mouth has undergone major planform changes. A delta with approx. 1.12 km^2 of emerged land was created between 1957 and 1980 and an additional 1 km^2 of land has been added between 1980 and 2006. The sinuosity of the river changed only slightly: negatively (−1.1% i.e. meandering decreased) for the period from 1957 to 1980 and positively (+3.0%) for the period 1980–2006. Comparison of cross-sections at the hydrological gauging station showed that the deepest point in the river bed aggraded by 2.91 m for the period 1963–2009. The importance of sediment deposition in the stream and on its banks is related to land degradation in the upper catchment, and to artificial rising of Lake Tana level that creates a backwater effect and sediment deposition in Gumara River. Direct anthropogenic impacts (irrigation activities and building of dykes along the river banks) have contributed to the huge deposition in the river bed. Where the abstraction of water for irrigation is intensive, seepage water through the banks has contributed to river bank failure. In general, this study showed that changes to the planform at the mouth of the river and to the riverbed level are substantial. Moreover, the study indicated that the flood carrying capacity of the Gumara River channel has diminished in recent times.

1. Introduction

Many authors showed that the interference of humans on the natural environment influences the nature of the landscape processes and the rate at which they operate. The increasing extent of the human disturbances such as land use changes, urbanization, channelization, gravel and sand mining and hydraulic structures construction along or across the river have brought changes to river systems (Strahler, 1956; Wolman, 1967; Hammer, 1972; Graf, 1975; Hollis, 1975; Jansen et al., 1979; Simons, 1979; Williams and Wolman, 1984; Kondolf and Swanson, 1993; Kondolf, 1997; Surian, 1999; Reid et al., 2000; Kondolf et al., 2002; Surian and Rinaldi, 2003; Urban and Rhoads, 2003; Zheren, 2003; Julien et al., 2005; Vanacker et al., 2005; Galster et al., 2006; Clark and Wynn, 2007; Conesa-García et al., 2007; Kondolf et al., 2007; Slaymaker, 2010; Kiss and Blanka, 2012; Li et al., 2014). For instance, urbanization makes the flow contributing area impervious and as a result it generates high runoff which can have

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a power of changing the river channel characteristics’. The existence of water projects, sand and gravel mining activities, may also lead to increase or decrease the stream transport capacity and thereby aggradation or degradation processes could occur which impacts the planform and shape of the river.

There are numbers of dependent (sediment supply, stream discharge and vegetation) and independent (geology, climate, human and time) landscape variables (Hogan and Luzi, 2010) which have a decisive role in the fluvial processes. Channel morphology is the result of the combined influence of the dependent landscape variables, and the channel responds to changes in these variables by adjustments in one or many of the dependent channel variables (width, depth, bed slope, grain size, bedforms, sinuosity, scour depth) (Hogan and Luzi, 2010; Ibisate et al., 2011). In response to changes in streamflow and sediment load (dependent landscape variables), alluvial rivers are dynamic systems that adjust their geometry (Lane, 1955; Leopold and Wolman, 1957; Heede, 1980; Schumm, 1985; Simon et al., 2002; Heitmuller and Greene, 2009; Dust and Wohl, 2012). The width of the channel, for instance, changes significantly by increased and decreased bedload supply after land use change (Liébault and Piégay, 2001; Kondolf et al., 2002; Liébault and Piégay, 2002). Alluvial river beds are subjected to morphological changes during flood events with significant implications for the water level (Neuhold et al., 2009). These changes may be the result of altered catchment hydrology or sediment supply, construction of riparian training structures, or channel alterations to support navigation or environmental needs (Scott and Jia, 2005; Blöschl et al., 2007). The stream corridors strongly depend on the river morphological processes and hydrological conditions, as well as on the catchment geology, topography, climatology, vegetation cover, land use practices and human interventions (Globevnik, 1998). During the preparation of flood hazard maps, it is generally assumed that the river morphology will have changed neither during flood events nor by long-term erosion or deposition. However, quantitatively and qualitatively observed morphological developments during and after flood events indicate changes in river bed elevation due to sediment transport, log jams or rock jams (Neuhold et al., 2009). The morphology of an alluvial river channel is the result of net sediment entrainment and deposition in the river (Russell, 1954; Strahler, 1956; van Rijn, 1984; Gaeuman et al., 2005; Paola and Voller, 2005; Church, 2006; Conesa-García et al., 2007). The sediment, either from the catchment or from the channel bed and banks, might have huge contribution to aggradation in one location and degradation in another location. Erosion of stream banks and shorelines by piping, for instance, has very significant impacts on bank and shore stability (Hooke, 1979; Odgaard, 1987; Hagerty, 1991; Julian and Torres, 2006; Bartley et al., 2008; Langendoen and Simon, 2008). Therefore, understanding the stability of rivers is essential, and the first step to address stability problems is the study of morphodynamic processes (Klaassen and Masselink, 1992) and a clear understanding of the relation of channel pattern to river stability is required in the design of channels for mined-land reclamation and in the planning for channel modification (Schumm, 1985).

In geological times, the landscape of the upper Blue Nile basin, Ethiopia, has been modified in fundamental ways by the processes of erosion, transport and deposition of sediments (Conway, 1997; Bewket, 2002; Dumont, 2009). The sediment that is eroded from the upstream catchments has often been deposited in the river channel and at the same time during flooding with lesser depositional height (sediment distribution in wide area) in the alluvial and lacustrine plains too. Sedimentation in the river channel could reduce the flood carrying capacity of the stream channels. This might be due to changes of river morphology or as a result of land use and land cover changes (Poppe et al., 2013). Though obtaining documented historical information on floods in Ethiopia is hardly possible, interviews with local old people and existing local documents have indicated that flooding has been documented since 1964 and the floods of 1988 were particularly mentioned (ENTRO, 2010). For example in the Fogera plain, flooding is increasing, with major occurrences in 1964, 1988, 1993, 1994, 1995 and 2006. The Fogera plain is located at the east of Lake Tana, in the north central part of the Ethiopian highlands. One of the causes of flooding of the Fogera plain is believed to be bank spillover from major rivers (Gumara and Ribb) which are draining into Lake Tana; particularly the Gumara River channel has a low conveyance capacity (Mekonnen, 2009; ENTRO, 2010). This might have a significant contribution for sediment deposition in the river channel, on the banks and at the lake shore when floods coincide with high lake levels. The problem of sedimentation is evidenced by obstructions at the outlets of the main tributaries (Gumara and Ribb Rivers) to Lake Tana, which led to courses that shifted to another direction (SMEC, 2008). In the Northern Ethiopian highlands, particularly human activities (removal of natural and semi-natural vegetation) have led to an overall increase in erosion process intensity (Dejene, 1990; Zeleke and Hurni, 2001; Hurni et al., 2005; Nyssen et al., 2008) despite recent positive impacts of targeted interventions by the society (Nyssen et al., 2007).

Though quite a number of studies have been carried out in Lake Tana basin, the effects of the developmental activities and other natural and man-made phenomena on the morphology (channel adjustment) of the basin’s tributary rivers has not yet been addressed. In contrast to the lack of studies in the upper Blue Nile basin regarding the detailed understanding and documentation of the responses of the rivers to changes (man-made and natural), the available literature in the international context shows that studying river responses to changes will give an opportunity to know the dominant processes that make the banks to collapse and the bed to aggrade or degrade. This will be useful to address channel maintenance and restoration work along the river, to understand the present channel dynamics and predicting future channel evolution as these are a key steps in reducing flooding. Therefore, the general objective of this study is to investigate and analyze the response of rivers to sedimentation, erosion and change of flow regime in the upper Blue Nile basin. The study was focused on Gumara River and specifically the objectives were: to investigate the channel planform and vertical changes; to explore the drivers for these channel morphological changes; and to conceptualize the morphodynamic processes at stake so as to understand future changes to Gumara River channel.

2. Materials and methods

2.1. Description of the study area

The Gumara catchment is located within Lake Tana basin in Ethiopia (Fig. 1). River Gumara originates from the Guna Mountains south and east of Debre Tabor at an altitude of approx. 3250 m a.s.l. The river flows westwards for 132.5 km until it reaches Lake Tana. The level of this shallow lake, the largest of Ethiopia, is regulated since 1995–1997 by a flow regulation structure just at its outlet to the Blue Nile River, the Chara-Chara weir which increases the lake level by up to 2 m, particularly in the rainy season. A stakeholder analysis (McCartney et al., 2010) has investigated the consequences for downstream users along the Blue Nile (irrigation, hydropower, tourism) and for farmers and fishers on the lake shore; however the consequences of the backwater effect along major rivers in the lacustrine plain was not investigated.

The Gumara catchment covers a total area of about 1595 km^2. There are many small intermittent and perennial rivers and springs in the catchment, which flow into the main stem, Gumara River.