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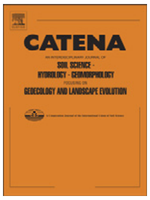

Sediment deposition patterns in a tropical floodplain, Tana River, Kenya

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ABSTRACT

Floodplains exert strong controls on downstream sediment transport and are as such important in material budgets of river systems. To understand sediment budgets in the Tana River, we investigated sediment storage along a 380 km floodplain reach (Garissa-Garsen) in the lower Tana River (Kenya), using a combination of approaches: (i) measurements of sediment deposition after an important flood event and, (ii) quantification of sediment storage using fallout radionuclide activities (^{137}Cs and ^{210}Pb$_{ex}$). Event-based sediment deposition ranged between 2-15 mm vertical accretion, corresponding to an average of 0.58 ± 0.42 g cm^{-2} (dry weight). Average annual sediment storage based on fallout radionuclide activities were at a 50 yr mean of 1.15-1.21 g cm^{-2} yr^{-1} and a 100 yr mean of 1.01 g cm^{-2} yr^{-1} (using ^{137}Cs and ^{210}Pb$_{ex}$, respectively). Sediment deposition rates were mainly dependent on distance relative to the main river, flood height and microtopography. The deposited sediments originated from various sources including deeply mobilized, radionuclide-poor sediments. Shallow overbank deposits (< 2 m depth), dominated by silty-clay sediment fractions were observed in most depositional areas. Floodplain sediment stocks are controlled by annual overbank flooding, with a 73 yr flooding frequency of 1.05 flood yr^{-1}. On average ca. 1-2 Mt (15-30%) of the river sediment load is deposited in the Garissa-Garsen floodplain reach. However, the overall channel dynamics including channel sediment storage and reworking are important and may have a very high impact on short-term sediment storage and release.

1. Introduction

River systems receive substantial quantities of sediment from their catchments, but rather than merely transporting the sediment load towards the coastal zone, they continuously deposit and rework sediments as they flow downstream (Day et al., 2008; Hoffman and Gabet, 2007). Both man-made structures such as reservoirs (Syvitski et al., 2005) and natural systems such as lakes and floodplains (Aalto et al., 2003; Noe and Hupp, 2009) are known to be key sites that exert strong controls on material storage and downstream mobilization. The exchange of sediment between the floodplain and the river channel is an essential component of the river system and even in relatively small catchments (<1000 km²), sediments may reside for >1000 yrs in floodplain environments before they are finally discharged at the river mouth (Hoffmann, 2015; Notebaert et al., 2009). While longitudinal studies of river sediment loads and biogeochemistry can provide important insights into the processing of sediment, carbon and nutrients during their residence in the river channel, a comprehensive understanding of the functioning of the system can only be obtained if the lateral exchange between the river channel and its environment is accounted for (Day et al., 2008).

Despite the fact that floodplain deposition is now widely recognised, data that would allow to us to quantify the relative importance are still scarce (e.g. Noe and Hupp, 2009; Swanson et al., 2008). This is especially true for non-temperate environments and this lack of understanding fundamentally limits our ability to predict the response of rivers to natural or man-made disturbances. In addition, current sediment yield models do not account for the buffering of sediments in alluvial or colluvial environments but relate sediment export to variables describing the catchment's state such as topography and land use on the one hand and climatic drivers on the other hand (e.g. Syvitski et al., 2005). For many catchments, such a direct relationship does not exist as sediments may be buffered for centuries, if not millennia, and this buffering should be accounted for when considering land-ocean material transport.

Understanding sediment erosion and transport within a catchment requires proper estimation of sources, sinks and outputs. For small catchments, quantification of these variables can be relatively easy to address leading to fairly accurate budgets (Hoffmann, 2015; Notebaert et al., 2009; Walling et al., 2002). However, erosion, transport and storage of materials in larger catchments is more difficult to quantify. In such catchments, fallout radionuclides offer a complimentary approach that allows estimation of sediments fluxes and budgets from various sources within the catchment (Wallbrink et al., 1998; Walling et al., 2002). Fallout radionuclides such as ^{137}Cs and ^{210}Pb are strongly sorbed

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by soil particles upon reaching the earth surface, their subsequent post-depositional redistribution is useful in tracing sediment mobilization. Assessment of their redistribution and storage within the catchment has been used to shed light on rates and patterns of sediment mobilization (Zapata, 2002). Complementary information may also be obtained from direct surveying of sediment deposits after a flood event (Gomez et al., 1995; Walling et al., 1997).

The major objective of our study was to quantify the amount of sediment deposited in the Tana floodplain in order to understand the impact of floodplain deposition on the river's sediment dynamics. We used a combination of these approaches to quantify the amount of sediment deposited and stored in a 380 km reach of the lower Tana River floodplains. We chose the lower Tana River for our study based on the fact that, the lower Tana River meanders for several 100s of kilometres, from the town of Mbalambala down to the town of Kipini, through extensive, semi-arid floodplains with no permanent tributaries, making it an interesting case to study river-floodplain interaction. Second, a number of recent studies in the Tana River have focused on the sources, transport, and processing of sediment and associated carbon in the stretch between the towns of Garissa and Garsen (Bouillon et al., 2009; Kitheka et al., 2005; Tamooh et al., 2013, 2014), providing a wealth of background data for this study. These earlier studies have demonstrated a substantial reduction in annual sediment and organic carbon fluxes between Garissa and Garsen, suggesting important floodplain storage (Tamooh et al., 2014).

We used fallout radionuclide inventories (^{137}Cs and ^{210}Pb$_{ex}$) on a series of sediment cores collected throughout the lower Tana floodplains to obtain long-term sediment storage rates. Secondly, we quantified sediment delivery into the floodplain by measuring the thickness of recent sediments deposits along transects perpendicular to the river course at various sections along the river. Based on calculated radionuclide inventories, we made a first-order estimate of the overall sediment budget in the lower Tana between Garissa and Garsen (hereafter referred to as the GSA-GSN reach) over the past decades and for the last major flood events, by combining this information with Landsat imagery and hydrological data.

2. Materials and Methods

2.1. Study area

The Tana is the largest river in Kenya, and flows ca.1,000 km from Kenya's central highlands of Mt. Kenya and Aberdare mountains (5800 m a.s.l) traversing the landscape to drain into the Indian Ocean at Kipini (Fig. 1). The catchment covers ca. 100,000 km² and can be divided into the headwaters (the mountainous streams from the Aberdare ranges, Mt. Kenya and Nyambene hills in the central parts of Kenya) and the lower Tana consisting of the section downstream of Kora where the river flows for ca. 700 km through semi-arid plains. The lower Tana has intermittent tributaries covering large catchments but only flowing in short pulses during the wet season (Maingi and Marsh, 2002). Three main seasonal rivers (Laga Tula, Laga Galole and Laga Tiva, Fig. 1), flow into the Tana River below the town of Garissa. The upper Tana catchment has five hydro-electric dams with a combined surface area of 150 km^2, and which are known to have influenced the downstream hydrology (Maingi and Marsh, 2002; Saenyi and Chemelil, 2003). The water in the dams has a residence time that varies between 3 months and 2 yrs, (Pacini et al., 1999). Recently, the dams have been shown to affect the seasonality of the discharge (higher average dry season discharge and lower average wet season discharge) but they do not appear to have a major impact on net sediment fluxes in the lower Tana due to the importance of autogenic sediment reworking (Geeraert et al., 2015).

2.1.1. Climate

The average annual precipitation varies from 2200 mm for the upper Tana catchment to 370 mm for the lower Tana downstream of Kora, with a gradual increase from 350 mm yr^{-1} at Garissa to about 470 mm yr^{-1} at Hola, and over 1000 mm yr^{-1} at areas downstream of Garsen (Brown and Schneider, 1996; see Fig. 1). Temperatures are on average above 30°C in the lower Tana, with a mean annual potential evapotranspiration (PET) between 1500–1700 mm (Dagg et al., 1970).

2.1.2. Geology

Geologically, the upper Tana catchment is underlain by a Precambrian basement complex, with volcanic formations mainly of tertiary age that originate from Mt. Kenya and the Aberdares. These volcanic rocks cover almost two thirds of the upper catchment. Downstream of Kora, the Tana is considered to be an alluvial river and is not constricted by outcrops of bedrock: therefore most of the meandering is determined by morphological processes (DHV, 1986).

2.1.3. Floodplains

The minimal elevation drop downstream of Kora has resulted in the formation of an extensive floodplain wherein the river is freely meandering. Flooding is common and usually associated with increased rainfall in the upper catchment and release of water from the dams. In the floodplain, a characteristic riverine forest fringes the banks of Tana River. The forest consists of a mosaic of deciduous and evergreen trees rich in endemic species (Hughes, 1988; Medley, 1992). The riverine forest extends for over 400 km of the Tana River from Mbalambala to Kipini and is dependent on flooding and ground water recharge.

Based on satellite imagery and Google Earth, the total recently active floodplain extent is ca. 998 km^2. The lateral extent of the GSA-GSN floodplain is rather narrow and varies between 0.2 km and 5 km, as compared to the Delta (below Garsen) where the floodplain extends up to 20 km from the main river. On the other hand, within the same GSA-GSN floodplain section, the river consists of one channel with a width that is fairly constant averaging between 50 m to 100 m. There are only minor changes in the valley slope between Garissa-Garsen, which averages ca. 0.5 m km^{-1} (DHV, 1986).

2.1.4. Hydrology and flooding

Two annual precipitation cycles occur in the basin resulting in a bimodal peak discharge and potential flooding frequency. The first of the two peak flows occurs between April and June (long wet season) and a shorter high flow period occurs during November/December (short wet season). At Garissa, daily discharge data based on gauge height and rating curves are available from 1941 to present. Flood flows generally range between 300-700 m^3 s^{-1} while base flow is at a mean of 75 m^3 s^{-1}. Occasionally extreme flood events with discharges over 1000 m^3 s^{-1} have been observed (WRMA, Water Resources Management Authority Kenya), (Fig. 2). Garsen discharge data are similarly based on gauge height and rating curves, it dates back to 1950s but with numerous gaps in the 1970s, and late 1990s to 2000s (supplementary information, Fig. S5).

2.2. Fallout radionuclides

Fallout radionuclides such as ^{210}Pb and ^{137}Cs have been widely used to calculate short-term (decadal time scale) sediment deposition and accumulation rates in different depositional environments. ^{137}Cs is an artificial or 'man-made' radionuclide; it has a half-life of 30.2 yrs and was generated as a product of thermonuclear weapons testing in the mid-1950s to the early 1970s. Other emissions are associated with nuclear accidents (e.g. Chernobyl in 1986). The use of ^{137}Cs as a sedimentation technique is based on the principle that sediment containing the nuclide derived from the upstream catchment is deposited downstream at a measurable rate. However, while ^{137}Cs provides a strong signal in sediment in the northern hemisphere, total fallout in the equatorial and southern hemisphere was only 25% that of the north and low activities are often observed. Nevertheless, various studies have also successfully used ^{137}Cs to estimate sedimentation in fluvial and lacustrine environments in the southern hemisphere (Amos and Croke, 2009; Hughes et al., 2009; Humphries et al., 2010).