Sediment yield of the lower Tana River, Kenya, is insensitive to dam construction: sediment mobilization processes in a semi-arid tropical river system

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Abstract

Dam construction in the 1960's to 1980's significantly modified sediment supply from the Kenyan uplands to the lower Tana River. To assess the effect on suspended sediment fluxes of the Tana River, we monitored the sediment load at high temporal resolution for one year and complemented our data with historical information. The relationship between sediment concentration and water discharge was complex: at the onset of the wet season, discharge peaks resulted in high sediment concentrations and counterclockwise hysteresis, while towards the end of the wet season, a sediment exhaustion effect led to low concentrations despite the high discharge. The total sediment flux at Garissa (ca. 250 km downstream of the lowermost dam) between June 2012 and June 2013 was 8.8 Mt yr^{-1}. Comparison of current with historical fluxes indicated that dam construction had not greatly affected the annual sediment flux. We suggest that autogenic processes, namely river bed dynamics and bank erosion, mobilized large quantities of sediments stored in the alluvial plain downstream of the dams. Observations supporting the importance of autogenic processes included the absence of measurable activities of the fall-out radionuclides ^{7}Be and ^{137}Cs in the suspended sediment, the rapid lateral migration of the river course, and the seasonal changes in river cross-section. Given the large stock of sediment in the alluvial valley of the Tana River, it may take centuries before the effect of damming shows up as a quantitative reduction in the sediment flux at Garissa. Many models relate the sediment load of rivers to catchment characteristics, thereby implicitly assuming that alterations in the catchment induce changes in the sediment load. Our research confirms that the response of an alluvial river to external disturbances such as land use or climate change is often indirect or non-existent as autogenic processes overwhelm the changes in the input signal.

Key words: sediment dynamics; autogenic processes; Tana River; sediment flux; external forcing

Introduction

Changes in the relationship between water discharge and sediment fluxes in rivers have often been used to infer changes in sediment supply due to variations in human pressure on the landscape (Dearing and Jones, 2003). The construction of reservoirs has often been found to result in decreased sediment fluxes downstream, a mechanism considered to override the effects of increased erosion due to land-use changes at the global scale (Vörösmarty et al., 2003; Syvitski et al., 2005). Another factor used to explain changes in the discharge-sediment flux relationship is climate: for example in the Yellow River (Huanghe) basin, 30% of the observed reduction in sediment fluxes over the past 60 years was attributed to a decrease in precipitation, the remainder being associated to reservoirs and soil conservation practices (Wang et al., 2007).

Such interpretations of sediment flux dynamics assume that changes within the catchment are directly translated into a change in the output signal, i.e. the sediment flux leaving the catchment. Such a direct coupling is also assumed in the models currently used to predict present or past sediment fluxes to the ocean. Without exception, these models use catchment characteristics such as average catchment elevation, land use, precipitation and climate to predict sediment yields at the catchment outlet (Syvitski and Milliman, 2007; Kettner and Syvitski, 2008; Vanmaercke et al., 2014). By doing so, they implicitly assume a steady state whereby changes in catchment conditions are directly propagated to the sediment flux at the catchment outlet. A similar line of reasoning is often maintained when interpreting sedimentary archives in alluvial plains and deltas, where the temporal evolution of sediments in the valley is often directly linked to land use changes on the catchment slopes and/or changes in climate (Macklin and Lewin, 2003; Hoffmann et al., 2009). Finally, catchment management plans often aim to reduce sedimentation in reservoirs by implementing soil conservation measures in well-targeted areas, again supposing that a direct link exists between sediment production and catchment yield (e.g. Hunink et al., 2013).

On the other hand, there is ample evidence that the response of rivers to changes in such external driving forces is not linear, and that considerably different responses to external forcing may be observed along a single river. Since the pioneering work of Schumm (1973), several papers have confirmed that the relationship between environmental change within the catchment and sediment flux at the catchment outlet is often indirect and may even be non-existent, even in small basins (Evans et al., 2000; Phillips et al., 2005; Fryirs et al., 2007; Fryirs, 2013; Nittrouer and Viparelli, 2014).

The inconsistent coupling between catchment characteristics and catchment sediment yields can be related to the importance of autogenic processes, i.e. processes taking place within the river channel, such as mobilization and deposition of river bed sediments and river bank erosion. Fluctuations in sediment transport rates occur even under steady boundary conditions as a result of such processes which are initiated once a threshold is reached (Jerolmack and Paola, 2010). Thus, rivers are not simply sediment conduits of hill slope derived sediments but may also act as buffers by storing sediments in alluvial plains for several millennia (Wittmann and Blanckenburg, 2009) and may supply sediment through channel enlargement or incision (Renwick et al., 2005). While it has become increasingly clear that autogenic processes have an important impact on the sensitivity of the river system to catchment changes (Syvitski et al., 2003; Phillips, 2013), little quantitative information is available to allow evaluating their role in explaining river sediment dynamics (Phillips et al., 2005). This is an important gap as the timing and the magnitude of the response of a catchment to environmental changes can only be well understood if the impact of autogenic processes is properly accounted for.

Assessing the relative importance of autogenic and allogenic processes in sediment mobilization and transport is difficult as, in most cases, it requires detailed measurements of sediment fluxes from the hillslopes entering the river system as well as detailed investigations of within-river sediment dynamics. In some cases, however, the relative importance of autogenic processes is easier to detect because there has been a major shift in the sediment regime due to human action and the response of the river can directly be monitored. The Tana River in Kenya is such a case. The high sediment loads in the upper Tana River have often been attributed to land degradation and soil erosion in the upper catchment (e.g. Ongweny, 1979; Ongwenyi et al., 1993). However, the sediment flux from the headlands to the lower alluvial river system was largely cut off by the construction of five large dams between 1968 and 1988 which effectively trap > 80% of all sediment produced in the Kenyan highlands (Brown et al., 1996; Bunyasi et al., 2013; Hunink et al., 2013). Ongwenyi et al. (1993) estimated the sedimentation in Kindaruma reservoir (before the construction of the upstream Masinga Dam) to be in the order of 6-7 Mm^3 y^{-1} (~9-11 Mt yr^{-1}). Later estimates of the sediment deposition in Masinga Reservoir were in the order of 8 Mt yr^{-1} (Hunink et al., 2013), which is the same order of magnitude (5.9-8.7 Mt yr^{-1}) as the present-day sediment fluxes measured 400 km farther downstream at Garissa (Tamooh et al., 2014).

The main objective of this paper is to investigate to what extent this natural experiment has affected river sediment fluxes in the Tana River downstream of the dams, and to determine the relative importance of autogenic processes in controlling the river's response through a detailed analysis of historical and recent sediment flux data, sediment ages, and a first assessment of sediment remobilization rates in the lower Tana River. Finally, we aim to provide a first quantitative estimate of the time scale over which the disturbance induced by dam construction may affect sediment fluxes at Garissa, where the discharge station is located.

1. Materials and methods

1.1. Study area

The Tana River is the largest river in Kenya (~ 1100 km long), draining an area of approximately 95 500 km² (Figure 1). The river originates in the highlands of the Aberdare Mountain Range (~3500 m) and Mount Kenya (5199 m). On its way to the ocean, between 900 and 770 km from the river mouth, the water passes through a cascade of five reservoirs located at altitudes between 1055 m (Masinga reservoir) and 700 m (Kiambere reservoir). The reservoirs, constructed between 1968 and 1988, were primarily installed to provide hydro-electricity and to a lesser extent for irrigation and discharge control. The catchment area upstream of the reservoirs is ca. 8500 km² (9% of the total catchment area). Between the dams and the beginning of the floodplain near Mbalambala, several perennial and seasonal tributaries, draining the eastern flank of Mt. Kenya and the Nyambene Hills and having a total catchment area of ca. 19 000 km² (20% of the catchment area), enter the main Tana

River. Further downstream, there are no permanent tributaries: the total drainage area of the ephemeral river systems (also called lagas) up to Garissa is ca. 4000 km² (4% of the catchment area). An extended and vegetated alluvial floodplain starts ca. 25 km upstream of Mbalambala at an altitude of ca. 250 m. From here on, the river meanders extensively with intermittent tributaries draining the arid savannah outside the floodplain, until it finally discharges to the Indian Ocean through a deltaic system. Many of the ephemeral streams are only active for a few days per year.

The catchment experiences two rainfall seasons per year: the long wet season between April and June and the short wet season in November-December. The spatial distribution of precipitation is highly variable with rainfall amounts up to 1800 mm yr^{-1} in the highlands, less than 400 mm yr^{-1} in Garissa and 600-1000 mm yr^{-1} near the delta (FAO, 2005; Knoop et al., 2012; MEMR, 2012). The interannual variability is also very high: in 1961, 1968 and 1997, Garissa received a total rainfall amount of more than 900 mm which is three times the annual average of 300 mm (Gadain et al., 2006). As a consequence of this uneven distribution, a disproportionate amount of the river discharge originates from the upper catchment.

The construction of the reservoirs has significantly impacted the hydrological regime of the river. In Garissa, where the most extensive dataset has been collected by government institutions (WRMA, Water Resource Management Authority), the peak discharges during the long wet season have declined by up to 20% (Maingi and Marsh, 2002). Discharges during the short wet season are unaffected, while the low flows during some months in the dry seasons have augmented up to 40% (Maingi and Marsh, 2002). Monthly average discharges in the post-dam period (1982-1996) ranged between 80 m³ s^{-1} and 302 m³ s^{-1} (Maingi and Marsh, 2002).

1.2. Sampling and analysis

Three types of new data were collected in Garissa for this research: (1) total suspended matter concentrations, (2) activities of the radionuclides ^{7}Be and ^{137}Cs, and (3) discharge measurements (Table 1).

Total suspended matter (TSM) concentrations were measured in Garissa by taking grab water samples in the middle of the river from 22/06/2012 to 21/06/2013 on a daily basis during most of the wet seasons and at least biweekly during the dry seasons (184 measurements in total). 25-200 ml of water was filtered on pre-weighed, pre-combusted (4 h at 450°C) 47mm Whatman GF/F filters (pore size: 0.7 µm). The filters were air-dried in the field and oven-dried at 50°C in the lab prior to re-weighing to determine sediment loads. The sampling period allowed us to sample the variation over the dry seasons (22/06/2012-8/10/2012 and 25/01/2013-19/03/2013), the short rains of 2012 (9/10/2012-24/01/2013), and the long rains of 2013 (20/03/2013-21/06/2013). The sediment concentrations were not corrected for concentration gradients within the river as additional sampling across the river profile showed that the concentrations did indeed not vary significantly with depth and with the lateral position (Data in Supporting information: Table S.1).

To determine activities of the radionuclides ^{7}Be and ^{137}Cs, daily suspended sediment samples were taken in Garissa during the discharge peak from May 2nd to June 22nd 2013, by filtering a sufficient amount of surface water on 100 mm cellulose-acetate filters (pore size 0.45 µm) to retain at least 1.0 g (dry weight) of sediment for analysis. After air-drying the filters, the sediment was put in the examination vials. A subset of 18 of these samples were analyzed for the activity of ^{7}Be and ^{137}Cs using an HPGe Well detector (Canberra) placed in a lead shield for at least 48 h. Samples were measured between 13 and 47 days after sampling with an average of 32 days. Given the half-life of ^{7}Be of 53 days, between 84% and 54% of the initial activity of ^{7}Be was still present at the time of analysis. Calibration of the detector was performed with IAEA standards (IAEA-RGU-1 and IAEA-385). The minimum detectable activities of ^{7}Be and ^{137}Cs were resp. 2.2 ± 0.3 Bq kg^{-1} and 3.1 ± 0.4 Bq kg^{-1}, based on background spectra.

Additionally, water height was recorded daily from a stage board at Garissa bridge. In order to translate water heights to discharge, five river cross profiles were measured at the bridge in Garissa with an Acoustic Doppler Current Profiler (ADCP, Teledyne RDI RiverRay) equipped with a depth sounder and GPS (GPS Hemisphere A100). Four measurements were taken during high water levels (May 9th, 10th, and 18th, 2012 and November 6th, 2012), and one measurement was taken on October 5th, 2012 just before the onset of the wet season. The ADCP measured water velocities over the entire river profile (accuracy of 2 mm s^{-1}) as well as the depth to the river bed (accuracy of 1%). These data were used to supplement an existing dataset of manual discharge measurements (using current meters) so that a rating curve could be established. Additionally, the ADCP profile data allowed us to assess the stability of the river cross section (see Discussion). It should be realized that, despite calibration, discharge estimates are always prone to some uncertainty as the cross-sectional area of the Tana River does vary through time (see Discussion).

1.3. Existing datasets

The new dataset is complementary to existing datasets: (1) historical sediment flux data in Garissa, (2) monthly measurements at three different sampling locations, and (3) single sediment concentrations at different locations along the river during three different seasons (Table 1).

Historical sediment flux estimates and corresponding discharge data from Garissa prior to the construction of the dams were reported in graphical form by Dunne (1988) for the periods 1948-1954, 1961-1962, 1963 and 1965-1966. The discharge and sediment flux data were digitized from a log-log plot and used to calculate corresponding sediment concentrations. It is important to note that in 1961, 1962 and 1963, severe floods occurred in the region.

Between January 2009 and December 2011, sediment concentrations were measured on a monthly basis at the outlet of the Masinga Reservoir, Kora, Garissa, and at the mouth of the Ura tributary (Tamooh et al., 2013, Tamooh et al., 2014, unpublished data) (Figure 1). The monthly measured sediment concentrations in Masinga dropped significantly (by a factor of 10) after June 25th 2010. The high sediment concentrations observed before this date occurred when the water levels of the reservoir were extremely low after a prolonged period of exceptionally low precipitation (Bunyasi et al., 2013). We hypothesize that during this period the residence time of the water was reduced due to the low water level. Therefore, less sediment was able to settle and/or scouring of the reservoir bed took place, both leading to higher concentrations at the outlet. Because of these exceptional conditions, only the data from Masinga with normal water levels (after 25/06/2010) were taken into account in the discussion.

Data on longitudinal variations in suspended sediment concentrations along the whole river course have been presented by Bouillon et al. (2009) and by Tamooh et al. (2012). We did not use all of these data, but limited ourselves to the lower river section, between the outlet of Masinga Reservoir and Garissa. At most of the sampling locations, Tamooh et al. (2012) took two sediment concentration measurements: one during the initial discharge peaks of the short wet season (October-November 2009) and one at the end of the long wet season (June-July 2010) when river discharges were already approaching dry season values. Bouillon et al. (2009) measured a single sediment concentration value for a subset of the locations used by Tamooh et al. (2012) during the dry season in February 2008.

1.4. Sediment flux calculations

Based on our own sediment sampling, the annual sediment flux for the period June 22, 2012 till June 21, 2013, was calculated by multiplying the daily discharge with the measured sediment concentration. For dates when no suspended sediment sampling had taken place (n=61, 12 and 108 for respectively short wet season, long wet season and dry seasons), the concentration was estimated based on 3 non-linear rating curves between sediment concentration and water discharge with a differentiation according to the season (Table 2). Alternative calculations based on discharge averaged concentrations, either per season, either over the whole year, indicate that the uncertainty on the annual flux due to the interpolation method is less than 5%.

The data used to construct the rating curves for the pre-dam period are incomplete: data do not cover a full year and the exact time at which a sample was taken is not known. Therefore, two methods were used to estimate annual sediment fluxes for the pre-dam period. In the first method a single non-linear rating curve was constructed for each observation period (Table 2). Daily sediment concentrations were calculated based on the daily discharge data provided by WRMA (Water Resource Management Authority, Kenya), and the summing of the daily sediment fluxes resulted in an annual sediment flux. The error on the annual fluxes is estimated to be ca. 3 Mt $yr^{-}1$, based on a comparison with fluxes calculated as the annual discharge multiplied by the discharge-weighted average concentration during the respective time period. The same method was applied for the monthly samplings of Tamooh et al. (2014).

The second method was based on the observation that the Tana River has two basic sediment regimes (see Results, Table 2). During low discharges, sediment concentration rises rapidly with increasing discharge (strong response). This is no longer the case when a prolonged period of high discharges occurs: after such a period, sediment concentrations drop and remain low for the rest of the wet season (weak response). We used two different rating curves to represent these distinct regimes. In order to estimate annual sediment fluxes, we always used the average strong response rating curve except for periods following a sustained wet period (i.e. discharges > 550 $m^3 s^{-1}$ for ≥ 5 days, until the discharge dropped below 150 $m^3 s^{-1}$) for which the weak response curve was used.

2. Results

2.1. Relationship between TSM and discharge

Our dataset contains records from two wet seasons: the short wet season of October-December 2012 and the long wet season of April-May 2013 (Figure 2a). During the short wet season, 5 individual discharge peaks, each lasting less than 6 days, were sampled for sediment concentrations while the second part of the short wet season was not sampled. The maximum discharge at Garissa during the short wet season was 650 m^3 s^{-1}, and no significant flooding occurred in the lower Tana River during this period. During the dry seasons, discharge was not constant but decreased slowly from 250 m^3 s^{-1} to 75 m^3 s^{-1}. In contrast to what was observed during the short wet season, the long wet season was characterized by a seasonal discharge pulse extending over ca. 2 months, on which minor individual discharge peaks lasting less than 5 day were superimposed. The maximum discharge observed in Garissa was ca. 950 m^3 s^{-1}, and resulted in an extended period of flooding throughout the lower reaches of the Tana River.

Suspended sediment concentrations also showed strong seasonal variations (Figure 2b). During the short wet season, each discharge peak resulted in a rise in sediment concentrations, leading to maximum values around 5700 mg L^{-1}. Throughout the dry season, the sediment concentrations were generally low, between 100 and 250 mg L^{-1}. During the long wet season, sediment concentrations rose again, and the peak values in sediment concentration, which were around 5000 mg L^{-1}, preceded peak values in discharge.

There was no simple relationship between discharge and sediment concentration (Figure 3a and b). However, if discharge peaks during the short wet season were analyzed in more detail, a clear counterclockwise hysteresis could be discerned for all individual peaks (Figure 3c). During the long wet season, seasonal variations were most prominent (Figure 3d). The strong decrease in sediment concentration at maximum discharge resulted in a clear seasonal clockwise hysteresis.

2.2. Comparison with pre-dam measurements

The combination of all available sediment concentration data indicated that there was a high variability in sediment concentrations, before as well as after the construction of the dams (Figure 4a). For discharges between 100 $m^3 s^{-1}$ and 500 $m^3 s^{-1}$, the variation in sediment concentration was very similar before and after dam construction. In the lower discharge range (< 100 $m^3 s^{-1}$), many more measurements were taken before dam construction and the sediment concentrations were higher compared to the measurements in 2009-2011. At very high discharges (> 750 $m^3 s^{-1}$) which most frequently occurred in the beginning of the 1960's, relatively low sediment concentrations were measured. The sediment rating curves for the different observation periods indicated two sediment regimes: one regime occurred in periods with sustained high discharges (>600 $m^3 s^{-1}$) during the wet seasons while a second regime occurred in periods where the river discharge rarely exceeded 500 $m^3 s^{-1}$, even during the wet season (Figure 4b and Table 2). The slope of the rating curves in the first regime was low (low response rating curves), as can be seen in the rating curves of 1961-1962, 1963 and 2013 (Figure 4b). For the second regime, the slope of the rating curve was much higher (high response rating curves). Rating curves did not show a clear shift due to dam construction (Figure 4b).

Given the limited information that is available with respect to the older measurements, we cannot verify whether the relative frequency with which these two regimes occur has changed due to dam construction.

2.3. Longitudinal variations in sediment concentration

The data from the monthly measurements were used to construct cumulative frequency curves and showed a clear distinction between the measurement stations (Figure 5). The sediment concentrations at the outlet of Masinga Reservoir were always significantly lower than those measured in Kora and Garissa, which are located 200 km and 400 km downstream of Masinga. At Kora, lower sediment concentrations occurred in comparison to Garissa during lower river stages. The systematic downstream increase in sediment concentration during low river stages period is a sign of an efficient sediment pick-up zone between Masinga and Garissa. However, during high river stages sediment concentrations at Garissa and Kora were similar, suggesting that sediment pickup mainly took place between Masinga and Kora. The data of the detailed longitudinal surveys confirmed that significant sediment pickup occurs immediately downstream of the reservoirs: at the Masinga Dam outlet, sediment concentrations were very low, both during the dry and the wet season (Figure 6). At Irira, which is located ca. 20 km downstream of the lowermost reservoir, a sediment concentration of 4500 mg L^{-1} was observed during the wet season of 2009. The longitudinal variations in sediment concentrations that were observed during this wet season survey were explained by discharge variations: samples at Irira, Usueni and Kora were taken during a falling stage, with progressively lower discharges. Samples downstream of Mbalambala were taken during the rising and peak stage of the consecutive flood peak.

2.4. Sediment fluxes

The calculated sediment flux at Garissa between June 22, 2012 and June 21, 2013 was 8.8 Mt yr^{-1}, based on 184 actual measurements. These measurements covered ca. 66% of the total sediment flux, as measurements were mainly carried out during flood periods.

Estimates of the annual sediment fluxes from 2009 until 2011 varied between 3.5 and 8.7 Mt yr^{-1} (6.7 Mt yr^{-1} on average), resulting in a total of 20.1 Mt for this observation period. This estimate is similar to the estimates derived by Tamooh et al. (2014) for the same period (17.7 to 26.1 Mt), which were calculated based on the same data using either a discharge weighted average method or a regression model.

The calculated annual fluxes for the pre-dam period (1948-1966) using the first method ranged between 2.5 and 12.2 Mt yr^{-1} except for one outlier of 31.6 Mt yr^{-1} in 1951, resulting in a pre-dam average annual flux of 9.4 Mt yr^{-1} (Figure 7). The high value in 1951 was likely an overestimate as the prolonged periods of high water discharge up to 700 $m^3 s^{-1}$ were expected to have resulted in a sediment regime requiring a low response rating curve rather than the high response curve which was used for the entire period 1948-1954. Using method 2, a similar range in values was calculated (range 2.2-14.2 Mt yr^{-1}, average 8.8 Mt yr^{-1}), whereas a much lower annual flux was obtained for 1951.

2.5. Fall-out radionuclides

^{7}Be and ^{137}Cs are fall-out radionuclides which are rapidly adsorbed to the fine fraction of surface sediments (Taylor et al., 2012). Due to the short half-life of 53 days for ^{7}Be and 30.1 yr for ^{137}Cs, the radionuclides can be used a proxy for recently eroded topsoil (Walling, 2013). Background topsoil values of ^{137}Cs in western Kenya range from 6.96 to 9.49 Bq kg^{-1} (DeGraffenried and Shepherd, 2009). However, we did not find measurable activities of ^{7}Be or ^{137}Cs in any of the suspended sediment samples that we analyzed. This suggests that the contribution of surface soils to the total amount of sediment present in the Tana River was minimal during the wet season of 2013 when discharges decreased from ~770 m^3 s^{-1} to ~150 m^3 s^{-1}.

3. Discussion

3.1. Rating curves and sediment flux calculations

The estimates of the sediment fluxes in Garissa before dam construction averaged 9.4 Mt yr^{-1} using method 1 and 8.8 Mt yr^{-1} using method 2 (Figure 7). Present-day fluxes at Garissa have an average of 7.2 Mt yr^{-1}. Evidently, there is a large uncertainty on our estimates of sediment fluxes, especially for the pre-dam period for which important information is lacking. Furthermore, sediment transport in the Tana River is characterized by important hysteresis effects (both over weekly and seasonal time scales), which are not fully accounted for when rating curves are used. Nevertheless, we believe that our estimates of the *average* sediment flux for the pre-dam period are robust as the results obtained using two different methods (one of which explicitly accounts for seasonal hysteresis) are very similar.

Thus, we may conclude that the annual sediment flux in the lower Tana River was not strongly affected by reservoir construction. This is remarkable, as the sediment retention in the Masinga Reservoir only was estimated at ca. 8.0 Mt yr^{-1}, based on bathymetric surveys (Brown et al., 1996; Hunink et al., 2013). Sediment retention in the whole series of five reservoirs is therefore likely to be equal to or even exceeding the annual sediment flux of the Tana River at Garissa.

Although there was no clearly observed change in the sediment fluxes at Garissa, there can still be a change in the sediment composition and grain size distribution if the source of the sediment has changed. It is not possible to determine to what extent this has been the case due to lack of information on historical sediment characteristics.

3.2. A conceptual model to explain sediment dynamics in the lower Tana River

A model of the sediment dynamics in the Tana River which can explain why the sediment flux was not drastically changed due to the construction of the dams, should account for the following observations:

1. The major part of the sediment transported by the upper Tana River into Masinga Reservoir is trapped behind the dams due to a trapping efficiency between 75% and 98% (Bunyasi et al., 2013), which resulted in very low sediment fluxes immediately below the dam. Nevertheless, the sediment concentrations at Garissa can nowadays still be as high as they were before dam construction, at least for discharges exceeding 100 m³ s^{-1} (Figure 4 and Figure 7).
2. The relationship between discharge and sediment concentrations is complex

and differs strongly between and within seasons (Figure 3). At the beginning of the wet season, sediment concentrations increased rapidly with increasing water discharge. This resulted in individual peaks, lasting several days, which were characterized by counterclockwise hysteresis. At a seasonal time scale, however, clockwise hysteresis was observed, provided that a period of sustained high discharges occurred.

3. The sediments transported by the Tana did not contain detectable amounts of ^{137}Cs and/or ^{7}Be, indicating that a major fraction of the suspended sediment was not originating from recent topsoil erosion.

First of all, a source of sediments needs to be identified which can compensate for the loss of sediment due to the dams. Hillslopes and tributaries downstream of the dams are definitely a source of sediment to the Tana River. The measurements at the Ura River outlet confirmed that these river systems can indeed carry significant sediment loads (between 25 mg L^{-1} and 3640 mg L^{-1}). However, there is no reason to assume that the contribution of these hillslopes and tributaries has changed due to the construction of the dams and one would therefore expect a significant reduction in sediment concentrations and annual sediment fluxes at Garissa if these systems were the only remaining providers of sediment to the main Tana River.

Therefore, a considerable amount of the sediment passing through Garissa must have been mobilized within the river and its alluvial plain downstream of the Kiambere dam (i.e. the last dam in the cascade). This would also explain the absence of detectable amounts of radionuclides in the suspended sediments during the wet season as most of these sediments were stored at depth and were not affected by radionuclide fallout.

It follows from the above that the additional sediment must be mobilized by autogenic processes. Furthermore, these processes are operating in such a way that both clockwise and counterclockwise hysteresis occurs, over different time scales (seasonal vs. weakly).

To explain the double hysteresis loops, the river cross section can be conceptualized as a rectangular to trapezoidal shape, representing the river bed and river banks which have certain resistance against erosion (Figure 8). Inside the river bed, point bars, sand bars and dunes are present and are made up of easily erodible sediment. The sequence of events over a cycle with one dry and one wet season can then be described as follows:

1) During the dry season, the river channel occupies only a part of the full river width due to low discharge: there are relatively large amounts of sediment present within the river bed as a result of sedimentation in the falling stage of the previous wet season. Sediment concentrations are generally low as the river is overdimensioned and little or no sediment is mobilized by lateral river migration and/or bed widening.
2) At the onset of the wet season and during following discharge peaks, river bed sediments which were deposited during the previous wet season are mobilized. During each discharge pulse, the channel is widened and deepened to accommodate the changing discharges. This sediment mobilization results in high sediment concentrations.

   The sediments that are mobilized during the rising stage of a discharge pulse travel, on average, somewhat slower than the river water due to deposition and resuspension cycles during the downstream transport. As a consequence, sediment concentrations at Garissa, which is located 200 km downstream of the beginning of the alluvial plain, will be higher during the falling stage than during the rising stage of the discharge peak, resulting in counterclockwise hysteresis.

3) Step 2 is repeated for subsequent discharge pulses until the river cross-section is again in equilibrium with the wet season discharge and a relatively stable cross section is achieved. However, even during this stage the equilibrium cross-section is still dynamic and the migration of river bends, with active bank erosion and point bar deposition still continues. As sediment concentrations during this stage are low in comparison to sediment concentration observed during the first discharge peaks of the wet season, a clockwise hysteresis is observed when considering the wet season in its entirety.
4) Finally, discharges start falling at the end of the wet season and the river cross-section will readjust to the dry season discharge regime. The storage of sediment within the river increases as the sediment that is mobilized by lateral erosion (bank collapse) can no longer be transported downstream and this sediment is therefore stored in sedimentary bodies such as point bars and/or bed forms.

The whole cycle is repeated during each dry season-wet season cycle, albeit that the nature of the wet season will evidently play a key role: if discharges strongly increase over a period of several weeks, river cross section adjustment will be more important and sediment stocks will be strongly depleted, resulting in low sediment concentrations during the last part of the wet season. If, on the other hand, the wet season only leads to a series of isolated discharge pulses each lasting 3-4 days, sediment stock depletion and stock replenishment at the end of the wet season will both be much less important, allowing sediment concentrations to remain high during the whole duration of the wet season. Thus, there is a balance between stock depletion and stock replenishment over several seasons.

3.3. Sediment supply

The model formulated above can only be correct if the river section expansion at the start of the wet season can mobilize sufficient amounts of sediment to keep the cycle going. Indeed, there is a net down slope transport of sediment, mostly during the rising stage(s) in each wet season, that needs to be replenished during the dry season.

The total sediment flux at Garissa between June 22nd, 2012 and June 21st, 2013, was estimated at 8.8 Mt yr^{-1}, and assuming a bulk density of 1500 kg m^{-3} for loose sands, this corresponds to a total sediment volume of ca. 5.9 10^{6} m^{3}.

The distance along the river between the last reservoir and Garissa is approximately 250 km, which means that on average 23 m^{3} yr^{-1} (m river length) $^{-1}$ has to be eroded (and replenished) to provide sufficient sediment for the observed sediment flux at Garissa. This is a maximum estimate as there is still a significant sediment supply from the tributaries and hillslopes which (partly) refill the alluvial sediment reservoir. Although these volumes of sediment are certainly significant, they do not require excessive morphological changes: if this sediment would have to be supplied by vertical incision only, the river would have to change its cross-section by 23 m^{2} (e.g. through a 0.23 m incision over its entire width of ca. 100 m). Assuming a vertical river bank height of 5 m, an overall lateral erosion of ca. 4.5 m yr^{-1} would be sufficient to deliver enough sediment.

Our ADCP profiles did confirm that the cross-section of the Tana River is highly dynamic and that important widening and some deepening did occur during the wet season (Figure 9). At Garissa, we measured a reduction in cross-section of 58 m² between the wet season in May 2012 and the end of the dry season in October 2012. This is considerably higher than our estimate of the minimum mobilization rate required: the latter is normal, given the fact that a lot of the mobilized sediment can be expected to be re-deposited before it reaches Garissa.

Lateral river migration is also important. Ndlovu (2013) studied meander migration rates in the Tana River just upstream of Garissa over a period of 35 years (1975-2010) by use of Landsat imagery. Migration rates for individual observation periods of 7 to 10 years varied between 4.1 and 10.4 m yr^{-1}. The longer term average (1985-2010) was 2.3 m yr^{-1}, suggesting that some changes observed over shorter time spans were annihilated over a longer time span. Assuming a total river bank height of 5 m, the longer term average river migration rate would result in the annual mobilization of 2.9x10^{6} m³ of sediments, showing that lateral river migration may indeed contribute significantly to the river's sediment supply.

It is also interesting to consider the fate of the natural sediment load from the upper catchment in the absence of the dams. The calculated fluxes and the sediment dynamics model indicate that, before dam construction, the lower Tana River was in near-equilibrium as the amount of sediment exported towards the delta was very similar to the amount of sediment coming from upstream. Autogenic processes were certainly active before the construction of the dams as the discharge regime was similar, but instead of mobilization of sediment being the dominant processes, the mobilization and deposition of sediment was of the same order of magnitude, keeping the sediment load near transport capacity along the entire lower Tana river. The sediment which is now trapped behind the dam was deposited within the floodplain, while older sediments were picked up in a dynamic exchange process.

3.4. How long will the sediment last?

The model we propose assumes that the river may locally be in a quasi steady-state, alternating between dry and wet season equilibrium. However, as there is an important net sediment flux at Garissa, there will be a net loss of sediments from the river system between Masinga and Garissa. So the question arises how long it will take before the trapping of the dams will be visible in the sediment flux record at Garissa.

A simple 1-box model, similar to the approach proposed by Hoffmann (2013) was developed where the box contains all the sediments in the floodplain upstream of Garissa (=storage, S) which are on the long term available for mobilization. The box has an input (I) and output (O) and the discrepancy between those is responsible for increase or decrease of the storage. While the input is assumed to be constant, the output is assumed to be in proportion to the storage according to a specific rate p, which is constant over time.

$$\frac{dS}{dt} = I - O(t) = I - p * S(t)$$

$$O(t) = p * S(t)$$

Solving the equation for the storage at time t results in

$$S(t) = \left(S_0 - \frac{I}{p}\right) * e^{(-p*t)} + \frac{I}{p}$$

With S(t) the storage at time t, S_0 the initial storage at time 0, I the constant input, p the specific rate and O(t) the output at time t. The specific rate is calculated based on the output and storage at t equal to 0.

In the baseline scenario, the initial floodplain sediment storage is calculated as the area of the floodplain upstream of Garissa (400 km², based on delineation of the floodplain area in Google Earth), multiplied by an estimated thickness of the alluvial sediments (10 m based on the depth soundings at Garissa, Figure 9). The initial output is assessed at 6.0 10^6 ton yr^{-1} and no sediment input at the upstream boundary was assumed as most sediment is retained in the reservoirs. To examine the sensitivity of the model towards the different variables (S_0, O_0 and I), three alternative scenarios were set up, whereby the value of one model variable was modified compared to the baseline scenario (Table 3): (1) the initial amount of stored sediment was reduced by 50% (e.g. because the thickness of alluvial deposits was overestimated) (2) the initial output was increase to 9.0 10^6 ton yr^{-1} (e.g. due to climate change), (3) there was a continuous input of sediment of 6.0 10^5 ton yr^{-1} (e.g. due to dam flushing and the contribution of the tributaries downstream of the dams)

We assumed that a change in sediment output became visible when it lowered to 75% of the initial output, i.e. to 4.5 10^6 ton yr^{-1}. Simulations show that the river-floodplain system will be able to buffer changes in sediment input for hundred to several hundreds of years, depending on the different scenarios (Table 3).

This time span can be compared with estimates of the life span of the reservoir system. After the construction of the first dams (Kindaruma in 1968 and Kamburu in 1974), it became clear that about 12.6 10^6 m³ had accumulated in Kindaruma between July 1968 and December 1970 (Ongwenyi et al., 1993), which implied that the life time of the reservoir was less than 20 years. The construction of Kamburu Reservoir and later Masinga Reservoir upstream of Kindaruma extended the life time of the downstream reservoirs. Upon design, the life time of Masinga Reservoir was estimated to be 500 years (Jacobs et al., 2007). However, it lost 6% of its capacity during the first 8 year of operation (Saenyi, 2004), and unless interventions are undertaken, complete siltation is expected to occur within 65 years (Jacobs et al., 2007).

3.5. Implications

The Tana River has two main characteristics which explain why the autogenic processes are dominant. First, the river has extended floodplains with a massive stock of sediments, which are a prerequisite for the necessary sediment buffering capacity. Secondly, the river has the possibility to rework these sediments because, despite the dams, there is still a clear alteration in discharges between dry seasons and wet seasons and the river has the freedom to migrate throughout the floodplain.

In large river systems where the external (human) impact had a clear impact on the sediment flux, at least one of these characteristics was not present. In the Nile River, like the Tana River, most of the sediment load is trapped behind the dams, but this sediment retention couldn’t be compensated for by sediment mobilization further downstream because damming also induced changes in the fluvial regime which severely reduced the peak discharges (Stanley, 1996). The Yangtze River experienced a strong reduction of the sediment flux because of dam construction, although the discharge regime remained relatively stable (Yang et al., 2011). Yet sediment loads were strongly reduced as autogenic river processes only compensated for only 20% of the amount of sediment retained in the dams (Yang et al., 2011). In this case the limiting factor was the absence of an easily mobilized sediment stock, as the river is disconnected from its floodplain due to the presence of an extensive levee system.

An example of a river system where both characteristics can be found is the lower Trinity River (USA) downstream of the Livingston Dam (Phillips et al., 2005). For 60 km below the dam, river incision and widening were observed. However, further downstream towards the delta damming had no discernable morphological effects, which was due to the large sediment storage capacity of the floodplain (Phillips et al., 2005). Also in the Mississippi River, the sand flux towards the delta will be unaffected by upstream dams for several centuries due to the sand stock that is present on the river bed (Nittrouer and Viparelli, 2014).

Our data show on the one hand that the annual sediment fluxes are confined within certain limits, and on the other hand that the annual water flux and its variability have a large impact on the variability in sediment fluxes. Both observations are important for catchment management: while the implementation of soil conservation measures will limit the sediment flux *into* the Tana River system, their effect on present-day sediment fluxes *within* the Tana River will be very limited. It follows from this that the effect of conservation measures cannot be assessed by measuring river sediment fluxes. At the same time, it should be realized that any modification of the water regime of the lower Tana River may have a significant impact on the amount of sediment transported by the river and may therefore have important consequences for the preservation of the Tana Delta ecosystem.

4. Conclusions

The comparison of historical and actual estimates of the suspended sediment load of the Tana River showed that no major change in annual sediment fluxes has taken place, despite the construction of five major dams in the upper catchment. The stability of the annual sediment flux can be explained as the result of sediment supply by autogenic processes, i.e. seasonal river bed incision and lateral river migration. Various observations supported the importance of autogenic processes: (1) a counterclockwise hysteresis was observed during individual discharge peaks, each lasting several days. However on the seasonal time scale, if water discharge was high over a longer time period, clockwise hysteresis was noticed. (2) the absence of fall-out radionuclides, indicating that the suspended sediment in the river is not recently eroded topsoil; (3) lateral river migration in the Tana River is very intense and is therefore an important source of sediment to the river; (4) the cross-sectional profile of the river changes considerably throughout the year.

An important requirement for the effectiveness of the autogenic processes is a sufficient supply of sediment that is easily mobilized. The available sediment stock will determine how long it will take before the construction of the dams will be visible in the sediment flux downstream. Based on a rough estimate of the available sediment stocks between the dams and Garissa and the actual sediment flux, we expect the appearance of the damming effects at Garissa to take several centuries.

These findings have implications for catchment management. Erosion reduction measures, which are generally implemented in the uplands, will have a limited effect on the downstream sediment flux in the case of the Tana River. However, water management decisions such as the reduction of peak flows due to dam buffering may have a noticeable impact on the timing and the magnitude of sediment transport towards the ocean.

Finally, current sediment yield models do not account for autogenic river processes: they assume a direct coupling between catchment characteristics and sediment load. These models cannot correctly capture the effects that human activity or climatic change may have on sediment yields for fluvial systems in which autogenic processes are important. In such systems, the response of sediment yield to human or climatic perturbations may be buffered for several centuries, if not millennia.

Conversely, identifying river systems in which autogenic processes are important may help to correctly evaluate such models. Over a longer term, accounting for autogenic processes in catchment sediment yield models would be an important step forward.

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Table 1. Overview of the different datasets on discharge and sediment load of the Tana river

Suspended matter measurements in Garissa

Number of observations	Time frame	Comments	Reference
184	22/06/2012-21/06/2013	Exact dates known Daily data during the wet seasons, at least biweekly during the dry seasons	This study
35	2009-2011	Exact dates known Monthly or biweekly data	(Tamooh et al., 2014)
32	1965-1966	Exact dates not known Digitized from log-log plot	(Dunne, 1988)
18	1963	Exact dates not known Digitized from log-log plot	(Dunne, 1988)
30	1961-1962	Exact dates not known Digitized from log-log plot	(Dunne, 1988)
127	1948-1954	Exact dates not known Digitized from log-log plot	(Dunne, 1988)

Locations of along-river measurements of suspended matter. At each location a measurement was taken during the dry season of 2008, the wet season of 2009 and at the end of the wet season of 2010.

Locations	Measurements per site	References
Masinga	1 per year	(Bouillon et al., 2009; Tamooh et al., 2012)
Irira	Id.	
Usueni	Id.	
Kora	Id.	
Mbalambala	Id.	
Saka	Id.	
Sankuri	Id.	
Garissa	Id.	

Monthly datasets of suspended matter

Locations	Number of measurements	Time frame	Reference
Masinga	18	06/03/2009-25/06/2010 (only normal water levels in the reservoir)	Unpublished data
Kora	34	30/01/2009-29/12/2011	(Tamooh, 2013; Tamooh et al., 2014)
Garissa	37	31/01/2009-30/12/2011	(Tamooh et al., 2014)

Ancillary data collection

Parameter	Time frame	Comments	Reference
Discharge	1948-2013	Daily at Garissa	Water Resource Management Authority, Kenya
River profiles	2012	5 measurements at Garissa	This study
Radionuclide activity ^{7}Be and ^{137}Cs	May-June 2013	18 measurements at Garissa	This study

Table 2. Regression parameters of the sediment rating curves. N is the number of observations, a and b the regression parameters in the formula $C=a.Q^b$. The last columns indicate the range of the discharge and sediment concentration of the observations for that period.

Period	N	a	b	R²	Range Q ($m^3 s^{-1}$)	Range C ($mg L^{-1}$)
Method 1						
1984-1954	127	60.5765	0.7336	0.48	23-613	130-11693
1961-1962	30	332.4511	0.1831	0.26	33-1880	380-2343
1963	18	227.4499	0.1452	0.18	90-1396	276-895
1965-1966	32	4.5897	1.0479	0.65	60-566	282-5217
2009-2011	35	1.7815	1.2857	0.28	32-398	81-9386
Method 2						
High response		74.6008	0.6575	0.36		
Low response		400.6040	0.1191	0.07		
2012-213						
Dry	55	0.8158	1.1233	0.25	87-169	77-309
Short wet	47	5.5089	1.0556	0.35	53-650	132-5725
Long wet	82	31.2337	0.6106	0.20	114-948	176-5396

Table 3. The time required in the different scenarios for the sediment load to decrease from the current sediment load (6 or 9 10^6 ton yr^{-1}) to 4.5 10^6 ton yr^{-1} at Garissa.

	Input (I) (10^5 ton yr^{-1})	**Initial storage (S) (10^9 ton)**	**Output (O) (10^6 ton yr^{-1})**	**Time to depletion (yr)**
Baseline	0	6.4	6	**307**
Scenario #1	**6**	6.4	6	**347**
Scenario #2	0	**3.2**	6	**153**
Scenario #3	0	6.4	**9**	**493**

Figure 1 and Figure 8 are supplied in black and white for the printed version and in color for the online version.

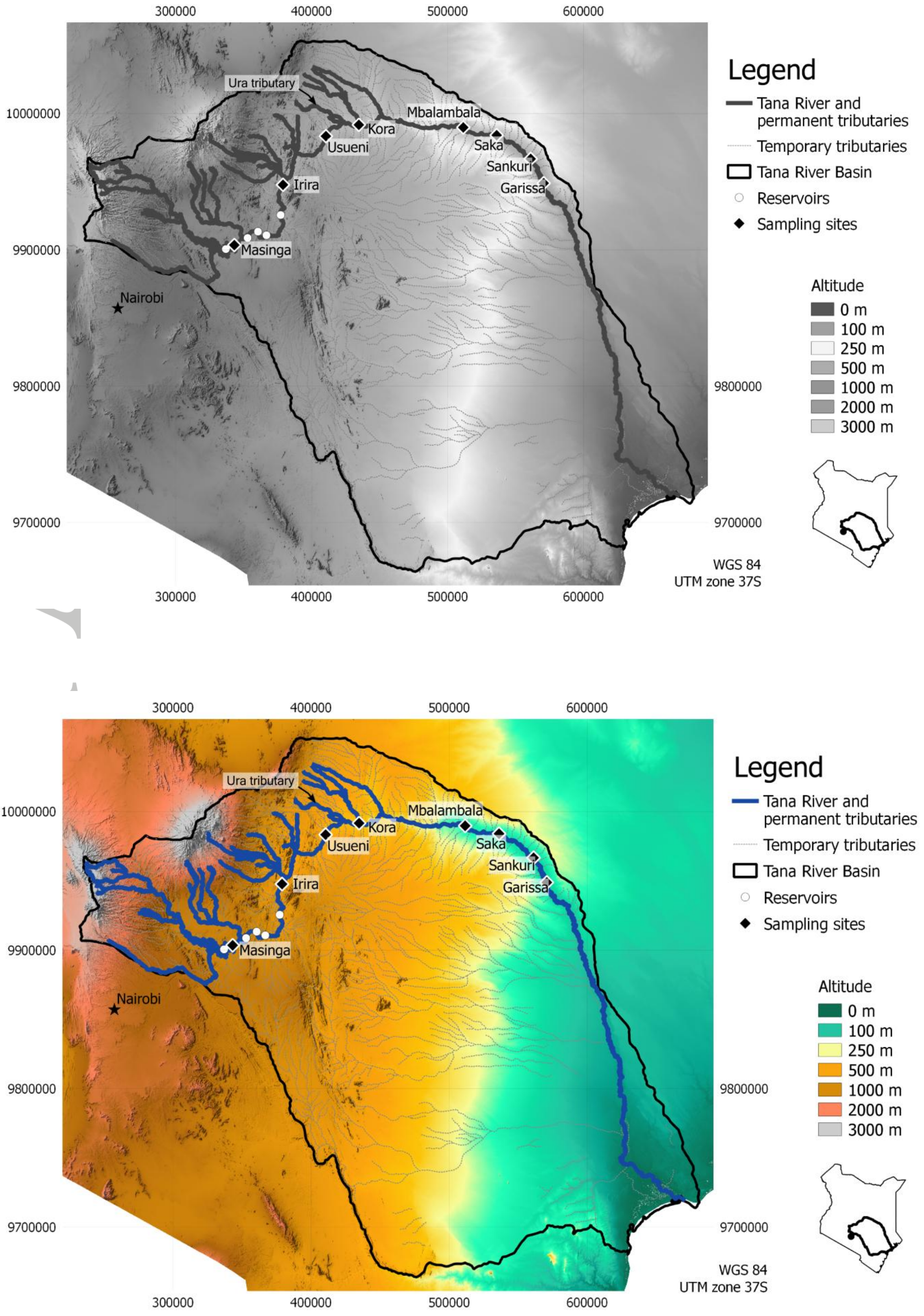

Figure 1. The Tana River Basin. The black diamonds are the sampling points along the longitudinal river profile (Figure 6).

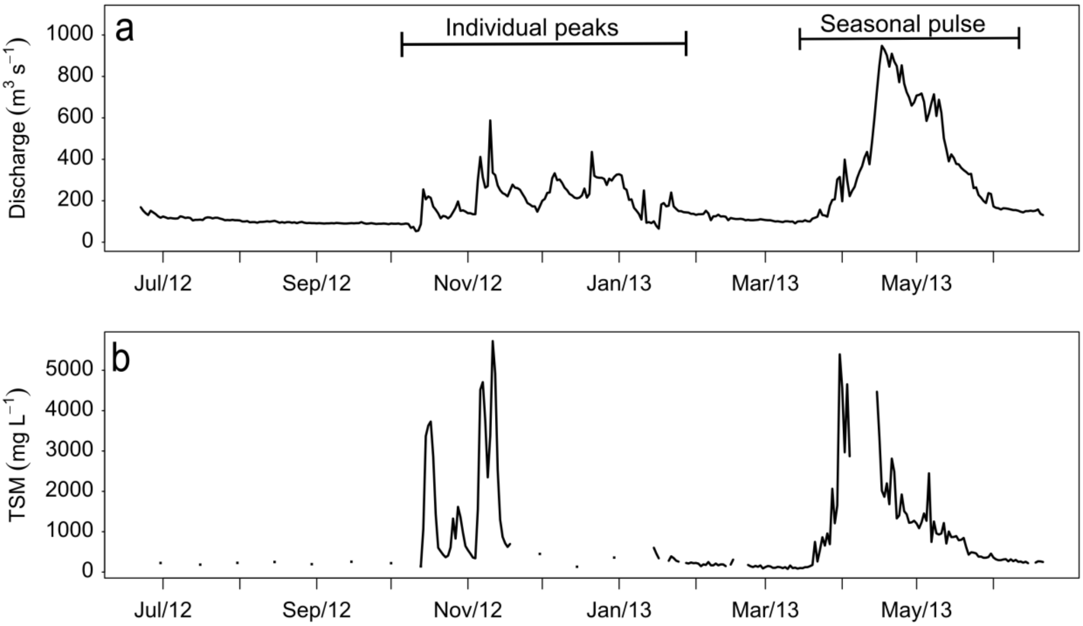

Figure 2. Time series of discharge (a) and total suspended matter (TSM) concentration (b) in Garissa. The individual discharge peaks occurred during the short wet season while the seasonal discharge peak occurred during the long wet season. TSM measurements on consecutive days are represented with a line to elucidate the pattern, while individual measurements are represented by points.

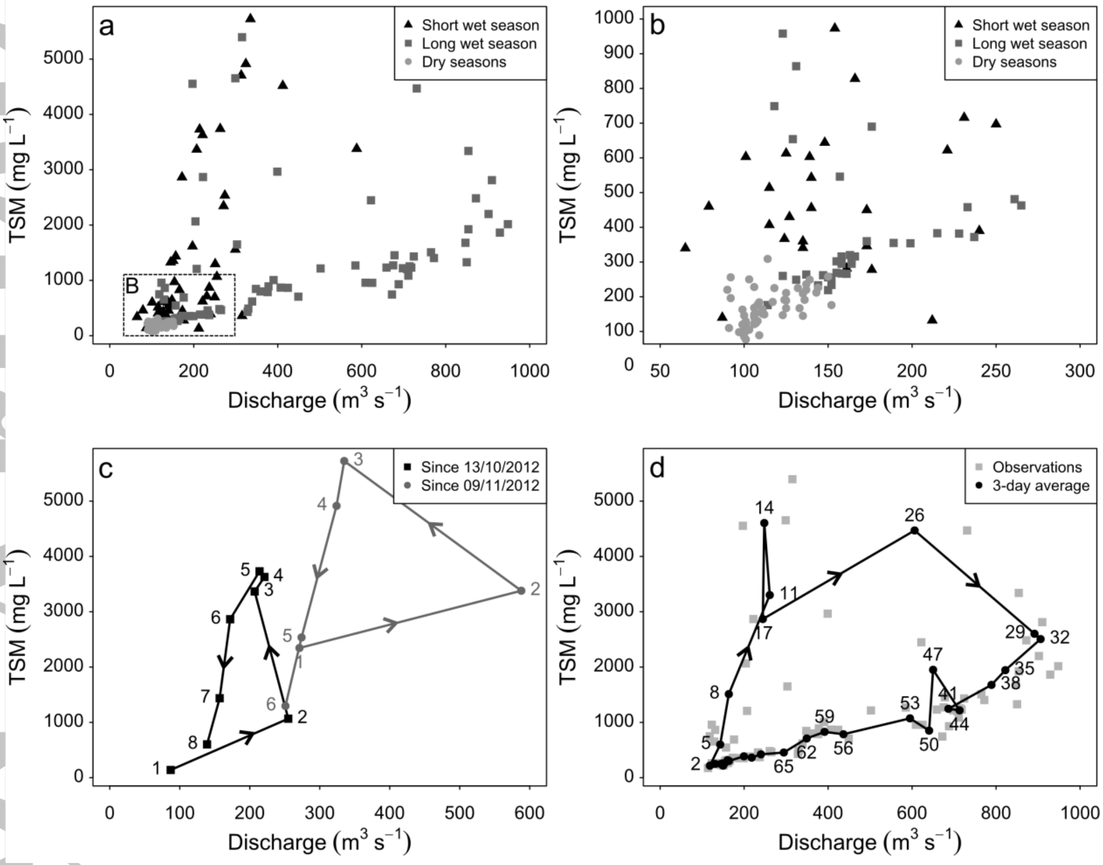

Figure 3. Variation of the sediment concentration with discharge between July 2012 and June 2013: (a) all observations; (b) detail of the low discharge-low sediment range; (c) details of the counterclockwise hysteresis during two discharge peaks in the short wet season. The numbers indicate the days since 13/10/2012 and 09/11/2012 for the squares and the circles respectively; (d) the seasonal clockwise hysteresis loop. The black points are 3-day average values of discharge and TSM. The numbers indicate the days since 20/03/2013.

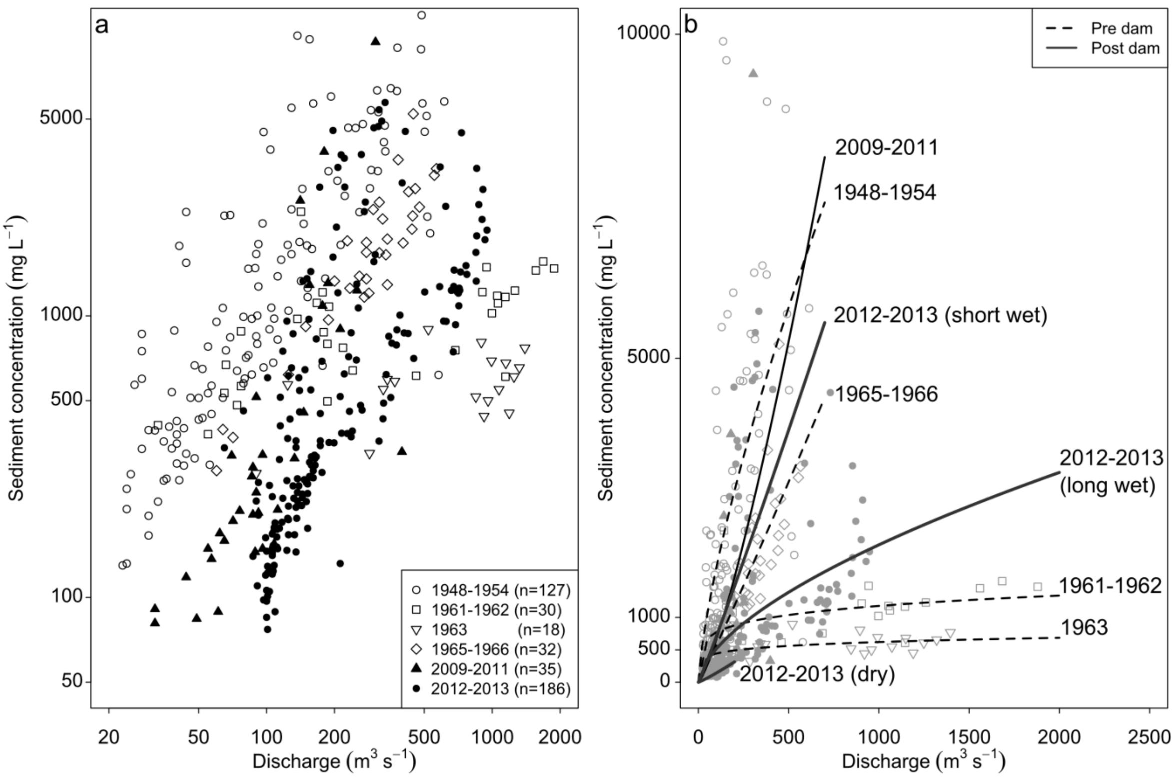

Figure 4. (a) Comparison of the sediment concentrations before the construction of the dams (open symbols) and after the dam (closed symbols); (b) The rating curves used for the calculation of the annual fluxes (method 1). Rating curve coefficients of both methods are summarized in Table 2. Note the log-log axes on the left figure, and the linear axes on the right figure.

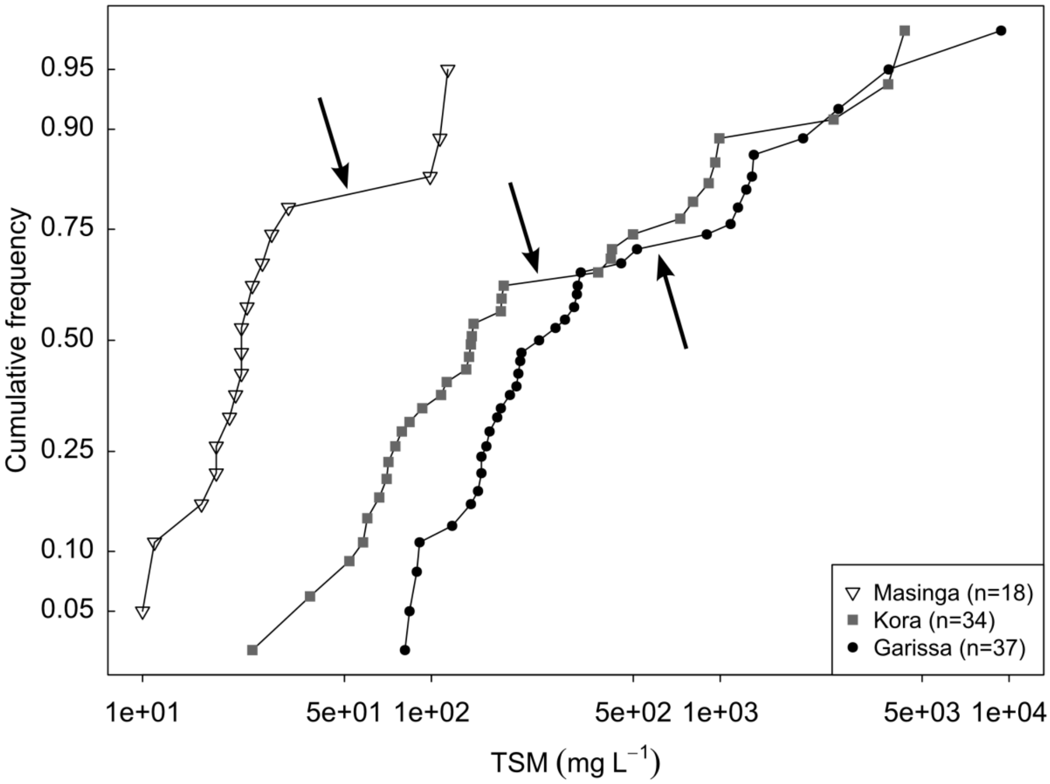

Figure 5. Cumulative frequency plot of the sediment concentrations at Masinga, Kora and Garissa collected by monthly samples from January 2009 till December 2011. The arrows indicate the break between low and high concentrations.

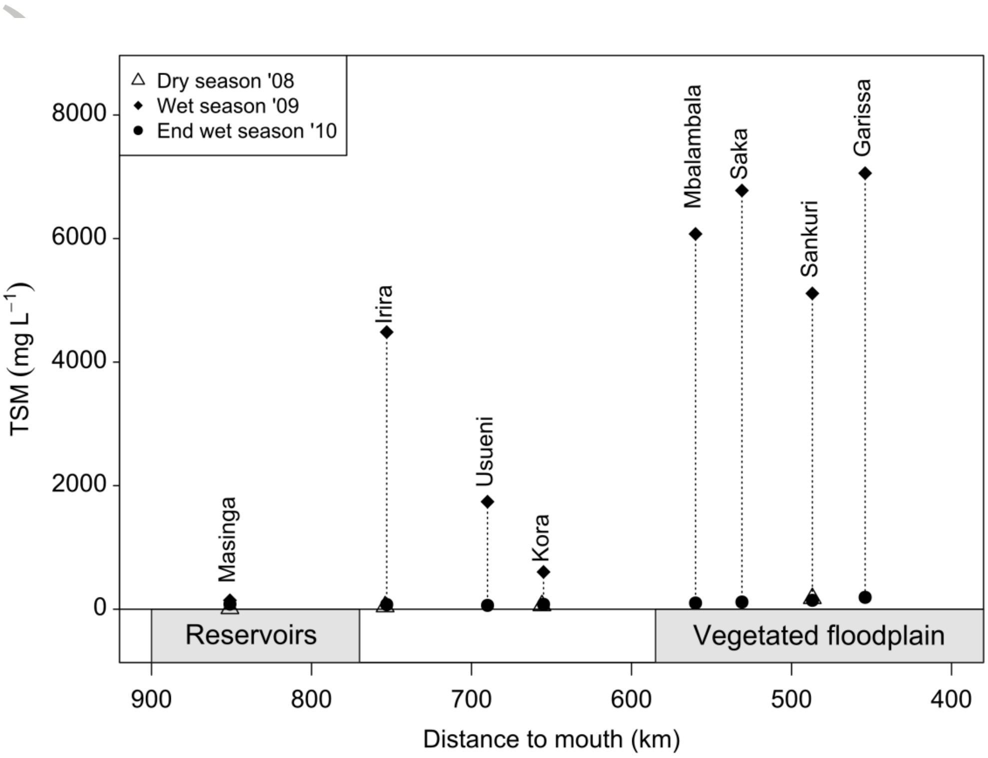

Figure 6. Sediment concentrations at different locations along the river between the outlet of Masinga reservoir and Garissa. (Data: Bouillon et al., 2009; Tamooh et al., 2012)

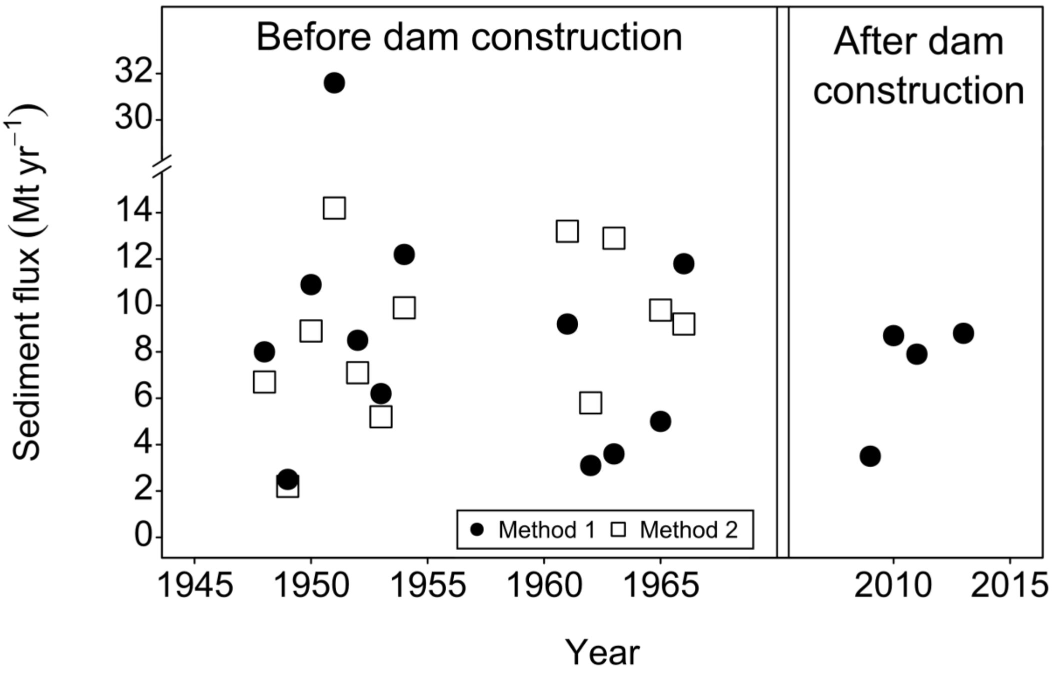

Figure 7. Estimation of the historical sediment fluxes at Garissa based on daily discharge data and rating curves based on the two methods (see text). Dam construction took place between 1968 and 1988. Note the broken y-axis to account for the outlier in 1951 with method 1.

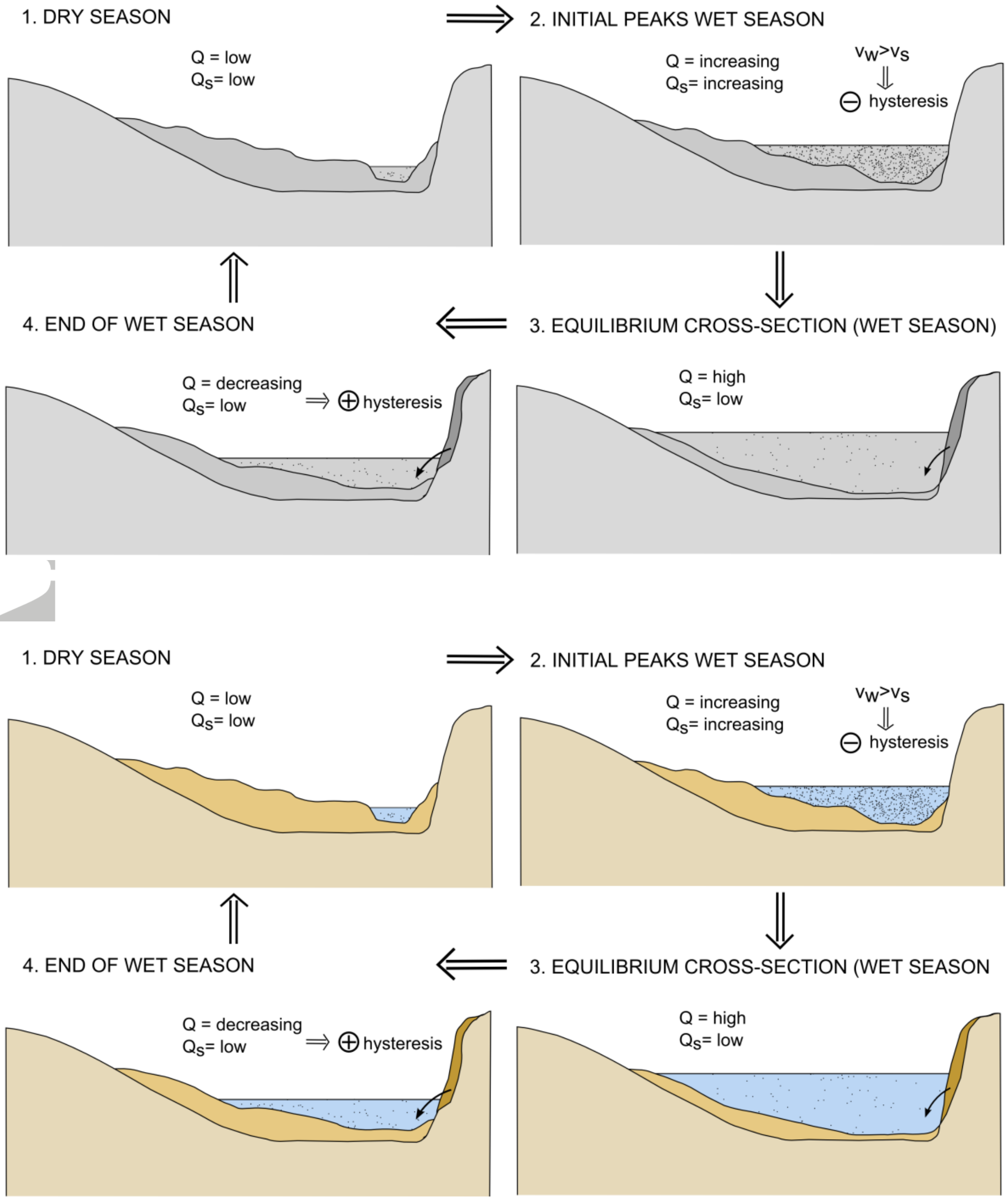

Figure 8. Illustration of 4 steps in the dynamics of the Tana River cross-section over the cycle of a dry and wet season, illustrating the autogenic processes of river bed mobilization and river bank collapse (Q is the water discharge, Q_s is the sediment discharge, v_w is the water velocity, v_s is the sediment velocity).

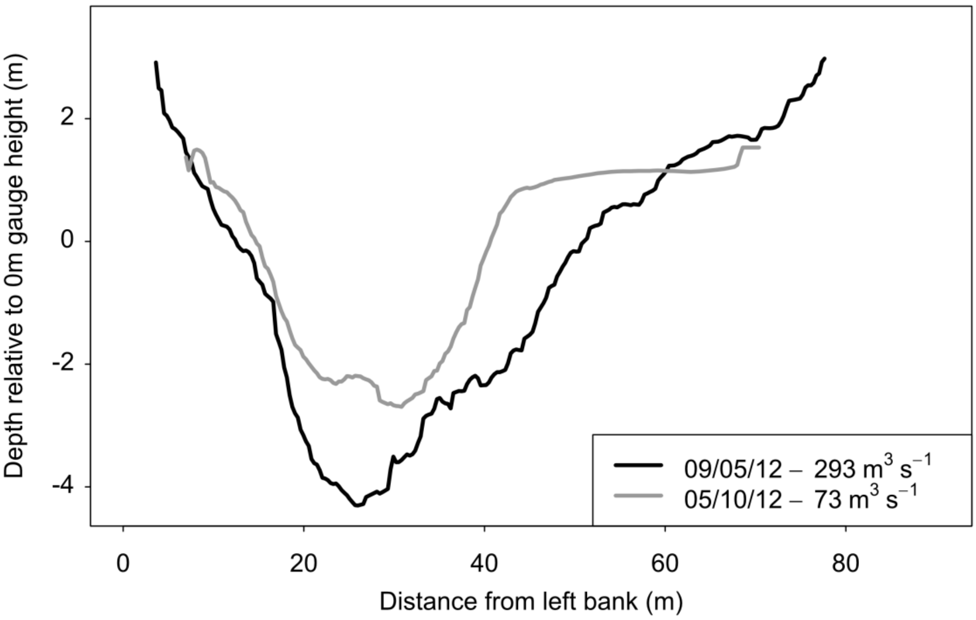

Figure 9. Change in cross-section of the Tana River at Garissa between the wet season (09/05/2012) and the end of the dry season (05/10/2012).