Published in final edited form as:

Geomorphology (Amst). 2014 June 1; 214: 366–377. doi:10.1016/j.geomorph.2014.02.018.

Rangeland management and fluvial geomorphology in northern Tanzania

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Abstract

Researchers have independently documented the effects of land use on rivers and threats to river management institutions, but the relationship between changes in institutional context and river condition is not well described. This study assesses the connections between resource management institutions, land use, and rivers by integrating social science, geospatial analysis, and geomorphology. In particular, we measured hydraulic geometry, sediment size distributions, and estimated sediment yield for four rivers in northern Tanzania and conducted semistructured interviews that assessed corresponding resource management institutions. Communities managed rivers through both customary (traditional, nonstate) and government institutions, but the differences in the resource management policies and practices of the study rivers themselves were fairly subtle. Clearer differences were found at broader scales; the four watersheds exhibited substantial differences in land cover change and sediment yield associated with the location of settlements, roadways, and cultivation. Unexpectedly, these recent land use changes did not initiate a geomorphic response in rivers. The long history of grazing by domestic and wild ungulates may have influenced water and sediment supplies such that river channel dimensions are more resistant to changes in land use than other systems or have already adjusted to predominant changes in boundary conditions. This would suggest that not all rivers will have the anticipated responses to contemporary land use changes because of antecedent land use patterns; over long time scales (centuries to millennia), the presence of grazers may actually increase the ability of rivers to withstand changes in land use. Our findings point to a need for further interdisciplinary study of dryland rivers and their shifts between system states, especially in areas with a long history of grazing, relatively recent changes in land use, and a dynamic social and institutional context.

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Keywords

dryland rivers; East Africa; hydraulic geometry; land use; resource management institutions; sediment

1. Introduction

Understanding the ways in which humans affect rivers has great practical importance for maintaining ecosystem function and resource availability. However, detecting river degradation and identifying its links to particular activities is challenging, especially because resource use rules often mediate the relationships between people and the environment. Failure to recognize these institutions and their relationship to resource-use decisions can result in substantial misunderstandings of the processes driving environmental change.

Rivers are especially valued features of arid and semiarid rangelands because of the ecosystem services they provide and the biodiversity they sustain. East African rivers, our focus here, support vegetation communities and wildlife assemblages that are distinct from the surrounding landscape mosaic (Medley and Hughes, 1996). Dry-season water and forage availability make them important habitats for consumers, and the spatial distribution of these resources structures wild ungulate migrations (Western, 1975), as well as livestock movements (Coppolillo, 2000). Yet East African rivers face threats from agriculture, resource extraction, damming, and settlement (Stave et al., 2001, 2003, 2007; Mango et al., 2011).

The effects of human activities on river channel geomorphology are well studied (Gregory, 2006). Channel dimensions and sediment size distributions are common metrics for describing river channels, whether to document natural patterns in undisturbed landscapes or as an indicator of possible adjustment to changing boundary conditions. Width to depth ratios (W:D) for dryland rivers range widely (3.8 to 255, Schumm, 1961; 16 to 340, Shaw and Cooper, 2008). Lower order streams and smaller drainages typically exhibit low W:D (Shaw and Cooper, 2008), and W:D is also inversely related to weighted mean percent silt-clay in the channel perimeter (Schumm, 1961). Channel dimensions can be affected by changes in land use that alter water and sediment supply from the surrounding landscape. The conversion of land to agriculture is associated with increases in flood magnitude (Knox, 1977), and additional loss of forest in the Mara River watershed (Kenya) is projected to decrease low flows and increase peak flows (Mango et al., 2011). Increased peak discharge yields more erosive stream flows that cause channel incision, especially in areas with fine, loose soils (Fu, 1989). Channel incision can then initiate a sequence of changes, wherein increased channel depth weakens riparian vegetation and stream banks, and can eventually lead to channel widening (Bull, 1997). Grazing is also a source of geomorphic change and has been associated with channel widening (Platts, 1991); similarly, livestock enclosure has been linked to decreased width, increased depth, and decreased W:D (McDowell and Magilligan, 1997).

In addition to these channel morphology changes are those affecting the sediment load and water load delivered from the watershed into the channel itself. The sediment size

distributions of riverbeds provide information on changes in sediment supply and transport capacity. Bedload particle size typically decreases in the downstream direction (Knighton, 1998), but changes in land use affect runoff as well as sediment delivery to channels (Clark and Wilcock, 2000), and in turn also impact in-channel erosion, sediment texture, and sediment transport (e.g., particle size, Pizzuto et al., 2000). Cultivation and rural roadways are significant sources of sediment in East African river catchments (Dunne, 1979).

Land use changes, and their effects on rivers, are mitigated by customary (traditional, nonstate-based) and by governmental resource management institutions. In East Africa, top-down rangeland management policies have, in many cases, marginalized traditional land tenure arrangements and land use patterns, often to the detriment of rangeland condition and local land users. In particular, government interventions have eroded systems of exchange, access, and mobility that had previously governed livestock distributions and range condition (e.g., Sandford, 1983; Fratkin, 1997; Homann et al., 2008; Mwangi and Ostrom, 2009). Customary systems for regulating riparian resource use have also been threatened by national policies that ignore indigenous knowledge and tenure arrangements (Stave et al., 2001, 2007). Recent efforts have recognized group property rights and decentralized land administration, but this too has been met with substantial challenges. In many places there are overlapping claims of tenure and conflicting resource demands across groups, and within groups there are problems related to power sharing, accountability, and equitability (Mwangi, 2009).

Although researchers have independently documented threats to customary resource management institutions and river systems in East Africa, there is a lack of research on the relationships between them. This gap in our understanding of the proximate and more distal drivers of river change limits our ability to effectively manage watersheds. As a result, this study asked: how do communities in northern Tanzania manage water resources, and what are the implications for river systems?

The goal of our study was to identify and describe the institutional governance of natural resources, and how those institutions affected fluvial geomorphic forms and processes. We thus used an integration of social science methodology, geospatial mapping, and standard fluvial geomorphic field work and analysis. The goal was not to develop novel methodology within any particular subfield but, rather, to understand how these subfields contribute to understanding the landscape that has been shaped by humans, their institutions, and ongoing natural processes.

2. Regional setting

East African rangelands support remarkable populations of wildlife, a network of world-renowned protected areas, and human communities. About 79% of the East African land surface is rangeland (Kenya 87%, Tanzania 74%, Uganda 79%) (Pratt and Gwynne, 1977). The rangelands of northern Tanzania and southern Kenya receive a mean annual rainfall of about 300 to 1200 mm (Gichohi et al., 1996). Annually, the climate regime is characterized by one long dry season from June to October and one rainy season from November to May,

which is subdivided into the short rains (November to January) and the long rains (February to May) (Prins and Loth, 1988).

The Simanjiro Plains, located in northern Tanzania, are semiarid with an average annual rainfall of about 600 mm. The vegetation consists of short grassland and smaller areas of woodland, bushland, and bushed grassland that is seasonally water-logged (Kahurananga, 1979). These savanna communities intergrade with riparian zones, which support remnants of tropical rainforest that became isolated and fragmentary because of climatic drying around 4000 YBP (Medley and Hughes, 1996). The soils of the Simanjiro Plains range from dark red sandy clay loam in the grasslands to black clay in the depressions (Kahurananga, 1981).

At the beginning of the wet season, wildlife — especially zebra (*Equus burchelli*) and wildebeest (*Connochaetus taurinus*) — migrate from Tarangire National Park (TNP) to the Simanjiro Plains (Kahurananga, 1981; Kahurananga and Silkiluwasha, 1997). As the dry season progresses, much of the wildlife migrates from Simanjiro back into TNP. Wildlife distributions are partly structured by water quality (particularly salinity; Gereta, 2004) and habitat and food preferences (Lamprey, 1963), but they are also attracted to TNP by surface water in the Tarangire River and the Silalo Swamp.

Water is a primary concern for Maasai pastoralists living in Simanjiro during drought and nondrought years. Streams and rivers are widely used water sources, particularly during times of water scarcity when boreholes break or become crowded, and dams dry up. When surface water is no longer available in rivers, hand-dug wells are used to access water for livestock, households, and even schools. Rivers and riparian zones are used for a variety of other purposes including washing, bathing, grazing, honey production, charcoal production, and as a source of building materials (timber and bricks). This study focuses on four rivers in Simanjiro: the Kikoti, Kiti Engare, Loiborsiret, and Terrat rivers (Fig. 1).

Livelihoods and land use in the study area have changed substantially in recent decades. This area is predominantly inhabited by Maasai pastoralists, who, in recent decades, have been diversifying their livelihoods through increased participation in agriculture and wage labor (Little et al., 2001; Thompson and Homewood, 2002; McCabe, 2003; Homewood et al., 2009; McCabe et al., 2010; Baird and Leslie, 2013). At the same time, there has been an influx of cultivators and commercial agriculture interests from other parts of Tanzania (Igoe, 2004). These changes have led to the expansion of cultivated land area and concern over the maintenance of wildlife migration routes between TNP and the Simanjiro Plains (Msoffe et al., 2011a,b).

Before assessing differences in land use and fluvial geomorphology across these rivers, it is necessary to account for the possibility that underlying biophysical variation could amplify or attenuate anthropogenic impacts on channel form. For instance, a confined bedrock river reach would likely have a lower channel width than an unconfined alluvial reach with the same level of human disturbance because bedrock reaches have less capacity for adjustment and are more resistant to change (Brierley and Fryirs, 2005). To ascertain the biophysical similarity of the study rivers and their capacity for channel adjustment, we borrowed

methods from stages 1 and 2 of the river styles framework (Brierley and Fryirs, 2005), classifying the rivers based on their levels of confinement, landscape units, and elevation profiles¹.

Preliminary fieldwork in 2009 and 2010 and initial geospatial analysis indicated that the four study rivers vary in terms of land use change but are comparable in other respects (Table 1). All rivers exhibit low slope angles and have a single active channel with predominantly sand/gravel bed material. Surprisingly, the drainage areas (calculated for the most downstream sampling points in each river) vary more widely; Kikoti River's drainage area is much smaller than the other three study rivers. However, the most remote study river (Kikoti) also appeared to be one of the least confined with the highest sinuosity, which suggests that comparing its channel geometry to that of other study rivers with the same relief and landscape position provides a conservative estimate of differences in anthropogenic impact on channel form. In addition, the four study rivers exhibit similar starting elevations, and sampling sites were located along a similar range of elevations in the rivers' profiles (Fig. 2).

Initial observations indicated variation in resource management institutions across the four rivers. The Terrat River appeared to have been subject to the highest levels of land use change, with cultivation across large parts of its catchment, settlement and roadways near the river, and ineffective regulation of grazing and resource extraction in the riparian zone. Kikoti is the most remote river and has also been managed as part of a grazing reserve. Loiborsiret and Kiti Engare have functioning riparian management institutions and intermediate levels of land use change. Loiborsiret's village center and main access road are located adjacent to the river, which has experienced more grazing pressure but less cultivation than Kiti Engare.

Based on these observations, we anticipated that the Terrat River would exhibit the most pronounced changes in channel dimensions and sediment, and the Kikoti River the least (Table 2). In particular, higher levels of land use change have been associated with channel incision in other systems, so we expected Terrat to have the greatest depth, followed by Kiti Engare, Loiborsiret, and Kikoti. We also hypothesized that rivers with higher grazing intensity in riparian areas (Terrat and Loiborsiret) would exhibit higher width. We expected that the Terrat River's channel area would decrease downstream as a result of scour upstream and deposition downstream, and Kiti Engare and Loiborsiret would show some initial signs of this reverse channel morphology. Sediment size was hypothesized to decrease downstream for all rivers following typical patterns of downstream fining. Since these are sand-/gravel-bed rivers and the parent material is mostly fine-grained sands and clays (Kahurananga, 1981), we expected that much of the moderately fine sediment would have been washed out of the upstream reaches of rivers that had been subject to more extensive land use changes. This was hypothesized to yield finer bedload sediment in Terrat, Kiti Engare, and Loiborsiret as compared to Kikoti.

¹We derived elevation profiles, slope estimates, and drainage areas from a 30-m digital elevation model (ASTER Global DEM) using the *TauDEM* extension for *ArcGIS 10.0*. This was the highest resolution, freely available DEM available for this remote region.

3. Methods

3.1. Resource management institutions

In order to identify and compare the institutions managing the four study rivers, 35 semistructured interviews were conducted with village leaders, key informants, and other community members from March to November 2011. Interviews were collected with the assistance of two Tanzanian field assistants who are fluent in English, Kiswahili, and Maasai.

Our assessment of institutions was guided by the design principles of long-lived common property resource institutions outlined by Ostrom (1990): clearly defined boundaries; congruence between appropriation and provision rules and local conditions; collective-choice arrangements that allow most individuals affected by the rules to participate in modifying them; effective monitoring by individuals who are part of or accountable to the resource users; graduated sanctions for users who do not respect community rules; conflict-resolution mechanisms that are cheap and easy of access; minimal recognition of rights to organize (e.g., by the government); and in case of larger common pool resources, organization in the form of multiple layers of nested enterprises. Interviews also addressed institutional responses to contextual and livelihood changes. A subset of interviews focused specifically on drought histories and changes in the use, management, and characteristics of the study rivers.

3.2. Fluvial geomorphology

We collected a total of 104 cross-sectional measures of river channel dimensions and 81 sediment samples within representative stream reaches across the four study rivers. Owing to Kikoti's small drainage area and short length, we were able to collect samples along nearly its entire length, whereas sampling of the other rivers was more restricted to their upper reaches. In terms of landscape units, all sampled reaches were in the uplands and foothills.

We used the active floodplain as the reference height for field measurements of channel width and depth. We identified the active floodplain by the presence of depositional features (e.g., break in bank slope, presence of perennial vegetation species, flat floodplain surface), and then quantified channel width, depth, and cross-sectional area. We also estimated sediment size distributions using the standard Wolman pebble count procedure (Wolman, 1954) and followed the common practice of describing bedload sediment using the particle sizes associated with the 84th, 50th, and 16th percentiles of the sediment size distribution (referred to as D_{84} , D_{50} , and D_{16} , respectively). We compared channel dimensions and sediment size distributions across rivers and in terms of their downstream trends. Downstream trends reflect temporal changes in water and sediment supply from the surrounding landscape and can thus aid in reconstructing the historical effects of land use changes on channel morphology. Evaluating the presence and magnitude of such downstream trends across catchments can demonstrate the environmental effects of different land use histories and help forecast future changes to river systems (Clark and Wilcock, 2000).

Lastly, we approximated sediment supply for each watershed using the Pacific Southwest Inter-Agency Committee (PSIAC) method of predicting watershed sediment yields (PSIAC, 1968). This method is similar to the Universal Soil Loss Equation but was designed for arid and semiarid conditions of the southwest USA (Graf, 1988). It has proven to be a reasonable estimator of sediment yield for various catchments in the southwest USA (Renard and Stone, 1982; Woida and Clark, 2001) and drylands elsewhere in the world (Safamanesh et al., 2006; Tangestani, 2006; de Vente, 2009). We collected GPS locations and rated nine factors (geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and sediment transport) at representative locations within major land cover types in each of the four watersheds. For each sample location, the sum of these nine rankings was entered as x into the equation

$$SY = 0.0816e^{0.0353x} \quad (1)$$

where SY is the annual sediment yield rate (acre ft mi^{-2}). We calculated mean sediment yield for each land use type within each watershed, and then estimated the sediment yield for each watershed by calculating an average weighted by the area of the different land cover types. Land cover classifications were derived from satellite imagery using a supervised classification method (Miller, 2013). Sediment yield estimates were not intended to be interpreted as precise values but rather approximations that allowed for comparison of relative differences in land use across sites.

Detecting the effects of land use on channel morphology can be confounded by shifts in precipitation; however, there have been no distinct trends in East African precipitation over the past 100 years, despite interannual fluctuations (Hulme et al., 2001). Moreover, climate and land use changes affect erosion of dryland rivers at different scales; variations in climate affect erosion at large scales, while land uses (such as grazing) control erosion in smaller catchments as is the case here (Graf, 1988).

4. Results

4.1. Resource management institutions

Both formal and customary institutions regulated natural resource use in Simanjiro. In terms of customary institutions, Maasai communities regulated the use of specific water sources through nested access rules. Maasai sections are social and political units that regulate access to large territories and thereby limited the use of grazing areas and water resources to people within broad geographical areas (Homewood and Rodgers, 1991). Clan (patrilineal group) membership regulated access to particular hand-dug wells that were 'owned' by individuals or households.

Wells were located in river channels or in the adjacent floodplain and could be quite deep (> 10 m), sometimes passing through layers of bedrock. Although wells filled with sediment each rainy season, people remembered the specific location of their well and excavated the infilled sediment every year. Well owners had priority access to water. People who did not own a well or who were from outside of the area typically used wells owned by individuals from the same clan. Nonowners had to request permission in order to use the well and were

assigned a day and time that they were allowed to use it. Livestock were typically watered every other day, and well users established an order of use for each day that was based on clan membership, village affiliation, and household location. In some cases, clans alternated the days that they used a particular well. Respondents generally viewed these institutions as effective at ensuring fair access to water and respected their processes and regulations. Establishing and following a specified watering schedule was particularly important because wells could take several hours to recharge after a group of livestock was watered. *Laigwenak* (age set² spokesmen) and other leaders were sometimes called upon to settle disputes associated with well use.

Formal institutions governed rivers at the broadest scale through national laws; for instance, people had to cultivate at least 50 m away from rivers. However, the village was the most relevant scale of government in terms of the specific rules, monitoring approaches, and levels of sanctions that related to daily household activities. Each village had three main committees: development, safety/security, and finance. These committees consisted of up to 25 members, including the village chairman, village executive officer, and subvillage chairmen. Committee members were from the village council, whose members were elected by the general assembly³. The district council oversaw village government decisions, but village-level rules were established through a process in which subvillage leaders collected recommendations from residents and brought them to the village council to formalize rules. These rules were then brought to the general assembly for final approval.

The three main village committees were composed of subcommittees (e.g., environment, health, school, wildlife, livestock, and water), and the village assembly appointed members to these committees every three years. We found substantial variation in the number and types of subcommittees in each village, and not all villages had water or environmental committees. Particular regulations also varied by village, and the governance structures associated with each of the four study rivers is described in greater detail below.

4.1.1. Kikoti River—The Kikoti River is located within Lolkisale Game Controlled Area. The GCAs regulate hunting; but settlement, grazing, and timber extraction are permitted within their boundaries (Caro et al., 1998). The management of Kikoti River fell under the jurisdiction of Loiborsoit village, which had an environmental committee and a water committee. The water committee was mainly responsible for the management of boreholes while the environment committee was in charge of a broader set of natural resources. Loiborsoit also established a subcommittee of the environmental committee known as the livestock committee. Their role was to regulate people bringing livestock into the village from elsewhere, mitigate environmental impacts from immigration and settlement, and ensure that the village benefited financially from these visitors.

²Age sets are male cohorts that pass through life stages or age grades (boy, warrior, junior elder, senior elder, retired elder) together, each stage having its own set of norms and responsibilities. During the warrior age grade, members acquire a name that identifies them as an age set and remains with them throughout their life (Homewood and Rodgers, 1991; Spencer, 1993).

³The general assembly consists of all residents of a village over the age of 18. This body elects a village council every five years. These councils can own property and engage in legal contracts (Nelson et al., 2007).

People from outside of Loiborsoit were only allowed to graze animals in the village during specified times. Those who entered the village during the grazing period had to ask permission to build a temporary settlement, and the committee selected the site. These individuals also had to move their animals once the grass in their area was depleted, and the committee assigned them a new location. Residents of Loiborsoit were also not permitted to use grazing reserves before approval by the committee. The village general assembly agreed upon a date when households should move their livestock to more distant grazing areas in order to conserve fodder near settlements for calves and smallstock. The timing of opening the grazing reserves varied by year and by local water availability. If someone moved into these areas without permission, they were fined and removed. Activities such as charcoal making were also illegal.

By and large, monitoring was the most significant problem facing the management of the Kikoti River because of the river's remoteness from the village center. On a few occasions the committee hired a vehicle for monitoring purposes, but the cost of doing so on a regular basis was prohibitive. As a result, they mostly depended on reports from other residents living in adjacent subvillages. It was widely believed that everyone had a responsibility to report unlawful activities to the committee and that community members would help monitor for violations because the resource-use rules were approved by the general assembly.

4.1.2. Kiti Engare River—Kiti Engare has a large watershed that spans multiple villages, but the active channel of the river is almost exclusively within the Kiti Engare subvillage of Sukuro. At the time of fieldwork, Kiti Engare was in the process of transitioning from a subvillage of Sukuro to an independent village with its own governance structures. It still shared some operations with Sukuro, and people from outside of the village were required to ask permission from the village council in order to access water sources. Kiti Engare did not yet have an environmental committee but was planning to establish one. This transitional period made the assessment of formal institutions difficult, partly owing to tension among residents regarding the Kiti Engare's split from Sukuro.

4.1.3. Loiborsiret River—Similar to Loiborsoit, Loiborsiret had an environmental committee that was responsible for managing natural resources, including forests, mining operations, and pasture. The environmental committee also provided the livestock committee with recommendations about grazing schedules and the placement of household compounds. In 2011, the committee also started collecting 'donations' from outsiders in exchange for grazing access.

The environmental committee was the primary body in charge of managing the Loiborsiret River and it established a number of use regulations, for example: settlement was prohibited within 100 m of the Loiborsiret River; livestock could not walk into the river and had to use the livestock trough; livestock could not graze on particular species of plants in the riparian zone; and people had to bathe and wash clothing at certain locations. The environmental committee was responsible for monitoring for rule violations, and the village office made decisions regarding punishment and sanctions for violators. As in other villages, all community members were considered part of the monitoring effort since everyone was

aware of the rules. The committee expected that if a resident found someone violating the rules, they would bring the offender to the village office, which was responsible for punishing violators. However, offenders were sometimes taken to *laigwenak*, and sometimes to the village council depending on the severity of the violation. For minor infractions, compromise could be sought with the committee or leaders; but for more serious violations (e.g., those involving violence), cases were taken up with the village office.

In terms of effectiveness of these institutions, herders generally followed the established order for watering their livestock at wells, keeping their animals in makeshift corrals until it was their turn to be watered. They also prevented livestock from grazing near the river. Yet despite these efforts, most of the grass in the riparian zone near the village center was depleted, either from trampling by the thousands of livestock that used wells in the river or from grazing by donkeys that were allowed to roam freely. Moreover, when the river was flowing, people could water their animals when and where they wished. According to respondents, the committee faced challenges with visitors violating village rules, conflicts related to the order of watering animals, and preventing charcoal making. Multiple community members expressed the view that although the committee was making an effort to sustainably manage the river, people continued to break the laws.

4.1.4. Terrat River—The Terrat environmental committee was responsible for managing the Terrat River and surrounding environments. Their primary role was to monitor for infractions such as tree-cutting, brick- and charcoal-making, the removal of gravel from the river bed, and bathing and washing in certain areas of the river. Violators were brought to the village office or the primary court for punishment. However, community members expressed concerns that the village council and the court did not assign sanctions that were commensurate with rule infractions identified by the committee, and as a result, the authority of the committee was limited. We heard reports of people being caught illegally grazing their animals in the riparian zone who did not receive any punishment. Charcoal and brickmaking were observed in several locations near the river, as well as gravel/sand extraction from the river channel itself. Problems with rule enforcement, largely stemming from poor coordination with the village council and court, had discouraged the committee from meeting frequently and fulfilling their duties.

The committee also had little agency in managing resources on land that had been allocated to households. The environmental committee was not responsible for land use planning — which was the purview of the land committee — and therefore could not impose sanctions on people for clearing forest on their land. The disconnect between environmental management and land use planning was also evident on a broader scale; people stated that the problems with the Terrat River were not from the management of the river itself but from the tributaries, which extend beyond the village boundaries where much of the land had been allocated and cultivated. Despite attempts to work with neighboring villages on land use planning, people often felt that there was simply too much demand for land and that people needed to cultivate. So although people in Terrat generally followed the rule that settlements had to be at least 70 m from the river, this buffer zone was, according to one community member, ‘...not enough to bring as much water as it used to.’

4.2. Channel dimensions and bedload material

Overall, we found no clear differences in channel geometry (Fig. 3). The Loiborsiret River had somewhat higher width, depth, and area compared to the other study rivers, especially in the upstream reaches, but mean W:D was similar for the four rivers (Kikoti = 10.0; Kiti Engare = 12.8; Loiborsiret = 9.5; Terrat = 13.0). The Kikoti River exhibited the most clear trends in downstream hydraulic geometry, but all rivers exhibited a downstream increase in channel dimensions. The relatively wide scatter of the data inhibits more detailed comparisons.

The Kikoti River exhibited higher values of aggregate D_{84} , D_{50} , and D_{16} compared to the other study rivers (Fig. 4). However, only the sampling distributions of D_{16} and D_{50} were significantly different across the four rivers ($p < 0.05$, Kruskal-Wallis equality-of-populations test). In particular, the D_{16} sampling distributions from Kikoti were significantly different than each of the other three study rivers ($p < 0.05$, two-sample Wilcoxon/Mann-Whitney rank-sum test). The D_{50} samples from Kikoti were also significantly different than those from Kiti Engare and Terrat at the $p < 0.05$ level, and significantly different from Loiborsiret at the $p < 0.1$ level. Moreover, Kiti Engare, Terrat, and Loiborsiret did not have significantly different sediment samples compared to one another.

Rivers had significantly different distributions of sediment across the Wentworth size classes ($p < 0.01$, χ^2 test) (Fig. 5). The proportion of sand and gravel in samples from Kikoti were significantly different than samples from each of the other three study rivers ($p < 0.05$, two-sample Wilcoxon/Mann-Whitney rank-sum test). Pairwise comparisons of the other three rivers indicated that their sediment distributions were not significantly different from one another.

We found a relatively clear pattern of downstream sediment fining in Kikoti, but this pattern was less pronounced for the other rivers. A comparison of the proportion of sediment in the 2–4 mm size class suggested that the presence of villages, road crossings, and cattle access points influence downstream patterns of sediment size, but this relationship was confounded by changes in bed slope (Fig. 6).

4.3. Sediment yield

The watersheds differed markedly in terms of the proportion of land cover in each land use class and in the calculated mean sediment yield of each class (Table 3). Additionally, the weighted mean sediment yield of each catchment was inversely correlated with D_{84} sediment size (Table 4).

5. Discussion

5.1. Resource management institutions

Communities in Simanjiro managed rivers through customary (e.g., clan-based access rules) and government institutions (e.g., environmental committees). Customary institutions facilitated negotiated access to resources and effectively limited disputes and resolved conflicts. The government institutions managing rivers in Simanjiro had arrangements that

allowed most individuals to participate in crafting rules. However, the roles of environmental committees were very broadly defined, and they had low capacity for monitoring and enforcement, often relying on monitoring from the resource users themselves.

Resource-use rules structure property rights (Schlager and Ostrom, 1992), and the mixture of government and customary institutions described above structured the rights of residents of the study villages, as well as the rights of herders from outside of the villages who brought their animals in search of water and fodder. Herders from outside of a village could obtain authorization from government institutions to access rivers and withdraw resources, whereas village residents not only had *de jure* (legal) rights of use but could also participate in resource management through rule creation and modification.

At the same time, Maasai held *de facto* rights to resources within their section's territory, regardless of their village membership. Within these territories, particular river wells were managed by households or groups of households that decided who was included/excluded from resource access and withdrawal. Nonowners could negotiate the right to use a well, but as water became scarce, some people were excluded from use based on clan affiliation or household location; this exclusion could be direct (i.e., explicit denial of access) or indirect (e.g., long waiting times). *De facto* and *de jure* rights to rivers in Simanjiro overlapped; Maasai sections and clans granted certain rights to some users, but villages could grant different rights to a different set of users. This suggests that government and customary institutions are not effectively coordinating their efforts.

Moreover, formal institutions are emerging that are taking on the roles of customary institutions. For instance, livestock committees regulated herders from outside the village, which was previously the purview of Maasai sections. The effectiveness of these new institutions was limited by the mismatch between administrative and ecological boundaries, and some community members continued to hold more respect for the authority of traditional leaders (e.g., *laigwenak*) than that of elected officials (e.g., subvillage chairs). These findings are consistent with studies from elsewhere in Tanzania and Kenya that have found that the institutions responsible for managing the environment have diversified and are at times at odds with traditional rules (Southgate and Hulme, 2000; Sokile et al., 2005).

The nested nature of Maasai customary institutions more closely matched resource boundaries and could provide a useful framework for managing resources across subvillage and village boundaries. The territories of Maasai sections are often closely related to geographical features such as watershed boundaries (Homewood and Rodgers, 1991). Moreover, the influence of *laigwenak* crosscuts administrative boundaries, which means they are in a position to coordinate the management of rivers and watersheds that extend beyond subvillage and village boundaries. Kiti Engare's transition from a subvillage to a village offers an especially valuable opportunity to establish formal governance structures that draw upon the strengths of existing customary institutions.

Overall, we found less variation in resource management institutions across the four rivers than initially expected, but the institutions managing the four study rivers face unique

challenges. Access to Kikoti was regulated based on the time of year and grazing conditions in other parts of the village, it therefore had the greatest congruence between appropriation and provision rules and local conditions. However, monitoring Kikoti is a substantial challenge because of its remoteness. The size of the Kiti Engare watershed raises concerns about the difficulty of managing land use impacts over a large area that spans multiple villages. In Loiborsiret, we found some coordination between customary and formal resource management institutions, but monitoring the Loiborsiret River during drought years is challenging because of influxes of large numbers of people and livestock from other villages. Moreover, punishment for violators was being decided on a case-by-case basis rather than through an established set of graduated sanctions. The environmental committee in Terrat had multiple problems associated with its role in monitoring and enforcement: no formal process for monitoring the river; inconsistent sanctions; poor coordination with the wider village government; and a substantial disconnect between private land use and watershed management.

5.2. Geomorphology and oral histories of river change

Each of the study rivers faces unique management challenges, but the differences in their resource management policies and practices were fairly subtle in terms of their influence on riparian resource use. More distinct differences were found at broader scales; the four watersheds exhibited substantial differences in land cover change and sediment yield associated with the location of settlements, roadways, and cultivation. So although it is not particularly surprising that the relatively subtle variation in river management was not associated with clear patterns in river morphology, it is interesting that the more substantial variation in land use across the four watersheds also did not yield more dramatic differences in channel geometry.

Despite the general agreement between our hypotheses and observations (Table 5), the differences between the rivers were much less pronounced than anticipated and, in some cases, contradicted our expectations. We found little evidence of channel incision or different downstream trends in channel geometry (Fig. 3). The W:D of the study rivers (9.5 to 13) were in the lower ranges identified by several previous studies of dryland rivers (3.8 to 255, Schumm, 1961; 16 to 340, Shaw and Cooper, 2008). Low W:D is typical for lower order streams and smaller drainages (Shaw and Cooper, 2008); but given that grazing has been associated with channel widening in other systems (Platts, 1991), it is surprising that all of the study channels exhibited low W:D despite widespread grazing and variation in grazing intensity.

We suspect that the absence of a clear relationship between land use change and channel dimensions is related to the long history of grazing by wild and domestic ungulates. Rivers in East African rangelands may have adjusted geomorphically to the long-term presence of large mammals and their associated effects on water and sediment discharge, making channels less sensitive to recent changes in land use. This resistance to land use changes would make it especially difficult to detect differences in river channel morphology across watersheds with relatively minor differences in resource management.

At this point in the system's trajectory, differences in bedload material appear to be more useful for detecting the influence of land use changes on rivers in Simanjoro. The sampling distributions of D_{50} and D_{16} were significantly different for the four rivers, and there was a significantly lower proportion of sand and a higher proportion of gravel in Kikoti River. These differences in sediment size may be indicative of the rivers' potential for more substantial shifts in geomorphology.

Because of this limited ability to discern trends using commonly used metrics of channel geometry, we used an alternative approach that examines estimates of channel changes through time, as developed by Clark and Wilcock (2000). Trends in the water and sediment transport capacity of the study rivers can be explored by integrating data on channel dimensions, sediment size, and sediment yield using the relationship

$$S_2/S_1 = (q_1/q_2)(q_{s2}/q_{s1})^{1/2}(D_2/D_1)^{3/4} \quad (2)$$

where S is bed slope, q is water discharge, q_s is sediment discharge, and D is sediment size at times, or in this case, different locations — 1 and 2 (Clark and Wilcock, 2000). If the ratio of slopes has a value < 1 , then this indicates degradation (i.e., lowering of bed slope from channel scour associated with increased water discharge, decreased sediment supply, and/or decreased sediment size), and > 1 would indicate aggradation (i.e., increased bed slope from sediment deposition associated with decreased water discharge, increased sediment supply, and/or increased sediment size). Clark and Wilcock (2000) used this approach to examine geomorphic adjustments associated with land use changes in Puerto Rico, and Schmidt and Wilcock (2008) used a variant of the approach to quantify the effects of dams on rivers in the western USA.

We present this relationship as a plot of D_2/D_1 versus q_{s2}/q_{s1} with constant q_2/q_1 ⁴ (Fig. 7). We use Kikoti as the reference site (i.e., location 1) for each of the other three study rivers and a hypothetical scenario (i.e., location 2). This space-for-time substitution approach has limitations (Pickett, 1989), but in the absence of historical data it is an available means of assessing river responses to land use changes in the study area. Moreover, this is a general relationship that is intended to make broad comparisons of sediment supply and transport across river catchments.

Kiti Engare, Loiborsiret, and Terrat had higher sediment supply ($q_{s2}/q_{s1} > 1$) and lower sediment size ($D_2/D_1 < 1$) relative to Kikoti. This combination of changes could allow the transport capacity of the rivers to remain relatively stable and yield little evidence of aggradation or degradation across the study rivers ($S_2 = S_1$; Kiti Engare, Loiborsiret, and Terrat data points in Fig. 7). However, if sediment supply increases further without dramatic changes in sediment size or water discharge (which both seem improbable), the channel likely will aggrade ($S_2 > S_1$; *Scenario* in Fig. 7). Slope could also increase through a decrease in sinuosity, which is possible in rivers with relatively weak channel margins (Clark and Wilcock, 2000).

⁴This is distinct from Clark and Wilcock's (2000) plot of q_{s2}/q_{s1} versus q_2/q_1 with constant D_2/D_1 . We deviated from their example because we collected data on sediment size, but did not have data on water discharge.

Oral histories from key informants and other residents of the study villages support this evidence for decreased sediment size and increased sediment supply, and are informative for reconstructing changes in land use and hydrology. The Terrat River has reportedly undergone a decrease in sediment size and a substantial decline in water discharge. In the past, the river was flowing throughout the year and now it only flows following heavy rainfall. Even during particularly dry years such as 1967 (*the year of the sun*), water could still be found on the surface of the river. Now people need to dig wells or move farther downstream in order to find enough water. The following statement from one community leader describes these changes:

There has been a big change in the Terrat River. When I was young it was flowing all year round, up to the road crossing. Now we have to go downstream, and there's not as much water. Even during droughts it was like the Loiborsiret River. There has been environmental destruction – cutting trees close to the river, cutting too many trees, not taking good care of the river – and the weather has changed. There is less rainfall. In the past people had to take livestock to certain places, now people come in wherever they want and walk in rivers. People aren't cultivating right around the Terrat River, but we depend on korongos⁵ to bring in water from other areas, and there is lots of cultivation in areas around these branches. The river is fed by three korongos that you can dig wells in... The river used to have sand in the branches, and now it's just mud; when it rains it brings mud... It's unusual to have mud; we expect to see sand, based on how it used to be. The branches are bringing sediment from farms. It's a problem along the whole river. There are also more people and more animals.

Declines in water availability were also reported for several other small drainages and for the Loiborsiret River. Perceived reductions in the amount of surface water may be related to relative declines in rainfall as well as changes in land use. Declines in rainfall are consistent with a period of unusually high rainfall in the late 1950s and early 1960s (Miller, 2013). However, changes in climate were not always viewed as the sole source of declines in water availability. Respondents often mentioned an increased number of people and livestock and land use changes as factors influencing the amount of water and sediment in rivers. For instance, people in Terrat pointed specifically to settlement and livestock watering sites near the village center; in the words of one man, 'it now looks like a livestock kraal.' Similarly, a group in Loiborsoit said that in the past there were large trees covered in moss that collected water, but people cut these trees and, as a result, rain was no longer collected and the sun dried out the ground. Following deforestation, more people started settling nearer to rivers. Some respondents also noted that increases in the amount of cultivated land had reduced the amount of water in some rivers.

These changes in water availability and sediment size may be the result of changes in water discharge similar to those observed in urbanizing systems. Urbanization can lead to '... increased volumes of runoff, decreased lag time between precipitation and runoff, and increased flashiness of flow (or increased kurtosis) of the runoff hydrograph' (Graf, 1988,

⁵Korongos are seasonal waterways or drainages.

286). Road building, cultivation, and settlement may have affected the study rivers in a similar fashion; land use changes could have led to more flashy flows (i.e., more contracted hydrograph with a higher peak discharge) that were capable of transporting larger sediment downstream while smaller sediment continued to be produced by fine-grained parent material (sandy clay loam in the grasslands and clay in depressions; Kahurananga, 1981). This explanation is not only consistent with the inverse relationship between sediment size and land use change in our study catchments, but also matches reports of decreased water availability. If water is now passing through the system more quickly than in the past (even given the same total amount of rainfall), it would appear as though rivers no longer flow for as much of the year as they used to.

A major challenge in managing the study rivers, and rivers in general, is the definition of resource units. Rivers are not only affected by resource use within the river channel, or even in the riparian zone, but instead are affected (via changes in water and sediment supply) by activities that take place throughout their catchments. Of the four rivers, Kikoti is the most clearly defined resource area because of its small size and geographic isolation from permanent settlements, whereas the watersheds of the other study rivers span multiple villages and encompass areas of permanent settlement. The institutions that are responsible for managing these rivers must coordinate their efforts with broader land use plans if they are to be successful at preventing substantial changes in river geomorphology.

5.3. Limitations

These findings should be interpreted in light of several limitations. First, the analyses of river channel geomorphology may have been complicated by different sampling extents. The short length of the Kikoti River allowed sampling of nearly the entire length of the channel, but we could only sample the upstream reaches of the other rivers. The selection of sampling sites was restricted by terrain, road access, dense vegetation, and the presence of potentially dangerous wild animals. Second, the surprising similarity of the Kikoti River's channel characteristics to those of the other rivers despite its very small catchment area suggests that Kikoti may be unique in other respects that we did not control for (e.g., underlying geology, groundwater hydrology). In the absence of floodplain stratigraphy data or high resolution soil maps, we cannot exclude spatial heterogeneity in geology as a possible explanatory factor in our analyses. For instance, a clay substrate may be limiting channel enlargement. It would be insightful for future studies to compare the floodplain stratigraphy of the four rivers in order to evaluate the effect of underlying soils and geology on the potential for channel changes. Third, lag times may hinder the ability to detect the effects of recent land use changes on river geomorphology, especially in semiarid environments where ephemeral channels only flow for brief periods of time each year. Finally, the Wentworth scale that we used for sampling sediment size distributions did not sufficiently capture variation in the finer sediments and did not allow comparison of the proportions of silts, clays, and sand.

6. Conclusions

Despite extensive grazing and more recent land use changes, rivers in Simanjoro have not responded as expected based on studies of other rivers. The long history of grazing by domestic and wild ungulates may have influenced water and sediment supplies such that river channel dimensions are actually more resistant to changes in land use (i.e., settlement, road building, and agriculture) than in other systems. This would suggest that not all rivers will have the anticipated responses to contemporary land use changes because of historical land use patterns, and it is possible that, over long timescales, the presence of grazers may actually increase the ability of rivers to withstand changes in land use.

However, the lack of evidence for a dramatic effect of contemporary land use change on river channel geomorphology in Simanjoro does not guarantee that these rivers will be resistant to further anthropogenic environmental effects. To date, reductions in sediment size may have counteracted the influence of increased sediment supply on bed aggradation/degradation, but continued increases in sediment supply in catchments like the Terrat River watershed are likely to lead to more pronounced changes in bed slope. Dryland rivers and ephemeral streams are dynamic, and there is a need for further study of shifts between different system states (Graf, 1988; Bull, 1997). Our findings show that this is especially true in regions with a long history of grazing and a relatively recent increase in nonirrigated agriculture. Social science, geospatial, and geomorphology methods can contribute unique insights to this research effort.

Maintaining river function and productivity requires particular attention to each river's institutional context. Maintaining the Kikoti River as a drought reserve is crucial for people and wildlife, and its remoteness from the village center necessitates increased capacity for monitoring. The Kiti Engare watershed spans multiple villages and will require broad coordination of land use planning, which could be facilitated by traditional leaders. Because Kiti Engare is splitting from Sukuro and becoming an independent village, it presents an opportunity to better integrate land use planning with river management. A large number of people and livestock converge on the Loiborsiret River during droughts, which necessitates a system for monitoring changes in resource availability during these periods, coupled with a consistent set of sanctions for rule violators. The efforts of Terrat's environmental committee are hampered by a lack of cooperation from other government organizations and by land use changes occurring on private land and on land beyond the village boundaries. It appears that the role and authority of Terrat's environmental committee needs to be more clearly defined and coordinated with land use planning in Terrat and in neighboring villages.

A common challenge in managing these rivers, and rivers in general, is the mismatch between the boundaries of watersheds and those of administrative units (e.g., villages). This mismatch necessitates collaborative approaches to land management. National laws and local rules regarding buffer zones around rivers are important, but not sufficient for managing water and sediment discharge. Discussions within and between communities about the collective influence of individual land use decisions on river systems could be constructive, especially in light of the belief that people may do what they wish on private land. Resource management institutions would benefit from more clear protocols for

monitoring, enforcement, and coordination across multiple institutions and locations; however, institutions in this region are frequently constrained by limited financial resources and infrastructure.

As government institutions take on increasingly larger and more diverse roles in resource management, it is important that they coordinate their efforts with customary institutions, which are widely respected and provide a consistent set of rules across administrative boundaries. At the same time, the resource management practices of multiple ethnic groups and the needs of various stakeholders will have to be balanced. Local nongovernmental organizations are in a good position to facilitate the coordination of customary and government resource management institutions.

Acknowledgments

We would like to thank Gabriel Ole Saitoti, Isaya Rumas, and Molly Dougherty for their tireless assistance in collecting data, and Paul Leslie, Pamela Jagger, Colin West, Aaron Moody, Richard Marston, and an anonymous reviewer for their helpful comments on previous drafts of this manuscript. Data collection was supported by a National Science Foundation Doctoral Dissertation Research Improvement Grant (BCS-1030847) and funding from the University of North Carolina at Chapel Hill and the Center for Global Initiatives. B.W. Miller is also grateful to the Carolina Population Center for training support (T32 HD007168) and for general support (5 R24 HD050924) from the Eunice Kennedy Shriver National Institute of Child Health and Human Development.

References

- Baird TD, Leslie PW. Conservation as disturbance: upheaval and livelihood diversification near Tarangire National Park, northern Tanzania. *Global Environmental Change*. 2013; 23(5):1131–1141.
- Brierley, GJ.; Fryirs, KA. *Geomorphology and River Management: Applications of the River Styles Framework*. Oxford, UK: Blackwell Publishing; 2005.
- Bull WB. Discontinuous ephemeral streams. *Geomorphology*. 1997; 19:227–276.
- Caro TM, Pelkey N, Borner M, Campbell KLI, Woodworth BL, Farm BP, Kuwai JO, Huish SA, Severre ELM. Consequences of different forms of conservation for large mammals in Tanzania: preliminary analyses. *African Journal of Ecology*. 1998; 36(4):303–320.
- Clark JJ, Wilcock PR. Effects of land-use change on channel morphology in northeastern Puerto Rico. *Geological Society of America Bulletin*. 2000; 112(12):1763–1777.
- Coppolillo PB. The landscape ecology of pastoral herding: spatial analysis of land use and livestock production in East Africa. *Human Ecology*. 2000; 28(4):527–560.
- de Vente, J. Ph.D. Thesis. Belgium: Katholieke Universiteit, Leuven; 2009. Soil erosion and sediment yield in Mediterranean geoeosystems.
- Dunne T. Sediment yield and land use in tropical catchments. *Journal of Hydrology*. 1979; 42:281–300.
- Fratkin E. Pastoralism: governance and development issues. *Annual Review of Anthropology*. 1997; 26:235–261.
- Fu B. Soil erosion and its control in the loess plateau of China. *Soil Use and Management*. 1989; 5(2): 76–82.
- Gereta EJ. Transboundary water issues threaten the Serengeti ecosystem. *Oryx*. 2004; 38:14–15.
- Gichohi, H.; Gakahu, C.; Mwangi, E. Savanna ecosystems. In: McClanahan, TR.; Young, TP., editors. *East African Ecosystems and Their Conservation*. New York, NY: Oxford University Press; 1996. p. 273–298.
- Graf, WL. *Fluvial Processes in Dryland Rivers*. New York, NY: Springer-Verlag; 1988.
- Gregory KJ. The human role in changing river channels. *Geomorphology*. 2006; 79:172–191.

- Homann S, Rischkowsky B, Steinbach J. The effect of development interventions on the use of indigenous range management strategies in the Borana Lowlands in Ethiopia. *Land Degradation & Development*. 2008; 19(4):368–387.
- Homewood, KM.; Rodgers, WA. *Maasailand Ecology: Pastoralist Development and Wildlife Conservation in Ngorongoro, Tanzania*. New York, NY: Cambridge University Press; 1991.
- Homewood, KM.; Kristjanson, P.; Chenevix Trench, P., editors. *Livelihoods, Conservation and Development in East African Rangelands*. New York, NY: Springer; 2009. *Staying Maasai?*.
- Hulme M, Doherty R, Ngara T, New M, Lister D. African climate change: 1900–2100. *Climate Research*. 2001; 17(2):145–168.
- Igoe, J. *Conservation and Globalization: A Study of National Parks and Indigenous Communities from East Africa to South Dakota*. Belmont, CA: Thomson/Wadsworth; 2004.
- Kahurananga J. The vegetation of the Simanjiro Plains, northern Tanzania. *African Journal of Ecology*. 1979; 17(2):65–83.
- Kahurananga J. Population estimates, densities and biomass of large herbivores in Simanjiro Plains, northern Tanzania. *African Journal of Ecology*. 1981; 19(3):225–238.
- Kahurananga J, Silkiluwasha F. The migration of zebra and wildebeest between Tarangire National Park and Simanjiro Plains, northern Tanzania, in 1972 and recent trends. *African Journal of Ecology*. 1997; 35(3):179–185.
- Knighton, D. *Fluvial Forms and Processes*. New York, NY: Hodder Arnold; 1998.
- Knox JC. Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers*. 1977; 67(3):323–342.
- Lamprey HF. Ecological separation of the large mammal species in the Tarangire Game Reserve, Tanganyika. *African Journal of Ecology*. 1963; 1(1):63–92.
- Little PD, Smith K, Cellarius BA, Coppock DL, Barrett CB. Avoiding disaster: diversification and risk management among east African herders. *Development and Change*. 2001; 32(3):401–433.
- Mango LM, Melesse AM, McClain ME, Gann D, Setegn SG. Land use and climate change impacts on the hydrology of the upper Mara River basin, Kenya: results of a modeling study to support better resource management. *Hydrology and Earth System Sciences*. 2011; 15:2245–2258.
- McCabe JT. Sustainability and livelihood diversification among the Maasai of northern Tanzania. *Human Organization*. 2003; 62(2):100–111.
- McCabe JT, Leslie PW, DeLuca L. Adopting cultivation to remain pastoralists: the diversification of Maasai livelihoods in northern Tanzania. *Human Ecology*. 2010; 38(3):321–334. [PubMed: 21915157]
- McDowell, PF.; Magilligan, FJ. *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*. Oxford, MS: University of Mississippi; 1997. Response of stream channels to removal of cattle grazing disturbance: overview of western US enclosure studies; p. 469–475.
- Medley, KE.; Hughes, FMR. Riverine forests. In: McClanahan, TR.; Young, TP., editors. *East African Ecosystems and Their Conservation*. New York, NY: Oxford University Press; 1996. p. 361–383.
- Miller, BW. Ph.D. Dissertation. Chapel Hill, NC: University of North Carolina; 2013. Linking conservation goals and outcomes: the social-ecological dynamics of drought resource management in East Africa.
- Msoffe FU, Kifugo SC, Said MY, Neselle MO, Van Gardingen P, Reid RS, Ogutu JO, Herero M, de Leeuw J. Drivers and impacts of land-use change in the Maasai Steppe of northern Tanzania: an ecological, social and political analysis. *Journal of Land Use Science*. 2011a; 6(4):261–281.
- Msoffe FU, Said MY, Ogutu JO, Kifugo SC, Leeuw J, Gardingen P, Reid RS. Spatial correlates of land-use changes in the Maasai-Steppe of Tanzania: Implications for conservation and environmental planning. *International Journal of Biodiversity and Conservation*. 2011b; 3(7):280–290.
- Mwangi E. Property rights and governance of Africa's rangelands: a policy overview. *Natural Resources Forum*. 2009; 33(2):160–170.
- Mwangi E, Ostrom E. Top-down solutions: looking up from East Africa's rangelands. *Environment*. 2009; 51:34–44.

- Nelson F, Nshala R, Rodgers WA. The evolution and reform of Tanzanian wildlife management. *Conservation and Society*. 2007; 5(2):232–261.
- Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action*. New York, NY: Cambridge University Press; 1990.
- Pacific Southwest Inter-Agency Committee (PSIAC). *Factors Affecting Sediment Yield and Selection and Evaluation of Measures for the Reduction of Erosion and Sediment Yield*. USA: PSIAC Report of the Water Management Subcommittee; 1968. p. 27
- Pickett, STA. Space-for-time substitution as an alternative to long-term studies. In: Likens, GE., editor. *Long-Term Studies in Ecology: Approaches and Alternatives*. New York, NY: Springer-Verlag; 1989. p. 110-135.
- Pizzuto JE, Hession WC, McBride M. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. *Geology*. 2000; 28:79–82.
- Platts, WS. Livestock grazing. In: Meehan, WR., editor. *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats*. Bethesda, MD: American Fisheries Society; 1991. p. 389-423.
- Pratt, DJ.; Gwynne, MD. *Rangeland Management and Ecology in East Africa*. London, UK: Hodder; 1977.
- Prins HHT, Loth PE. Rainfall patterns as background to plant phenology in northern Tanzania. *Journal of Biogeography*. 1988; 15:451–463.
- Renard, KG.; Stone, JJ. *Proceeding of the Workshop on Estimating Erosion and Sediment Yield on Rangelands*. USDA-ARS Agricultural Reviews and Manuals. Tucson, AZ: 1982. Sediment yield from small semiarid rangeland watersheds; p. 129-144. ARM-W-26
- Safamanesh R, Sulaiman WNA, Ramli MF. Erosion risk assessment using an empirical model of Pacific South West Inter Agency Committee Method for Zargheh watershed, Iran. *Journal of Spatial Hydrology*. 2006; 6(2):105–120.
- Sandford, S. *Management of Pastoral Development in the Third World*. New York, NY: John Wiley & Sons; 1983.
- Schlager E, Ostrom E. Property-rights regimes and natural resources: a conceptual analysis. *Land Economics*. 1992; 68(3):249–262.
- Schmidt JC, Wilcock PR. Metrics for assessing the downstream effects of dams. *Water Resources Research*. 2008; 44(4)
- Schumm, SA. United States Geological Survey. Washington, DC: 1961. Effect of sediment characteristics on erosion and deposition in ephemeral stream channels; p. 31-70. Professional Papers 352-C
- Shaw JR, Cooper DJ. Linkages among watersheds, stream reaches, and riparian vegetation in dryland ephemeral stream networks. *Journal of Hydrology*. 2008; 350:68–82.
- Sokile, CS.; Mwaruvanda, W.; van Koppen, B. Paper presented at the International Workshop on African Water Laws: Plural Legislative Frameworks for Rural Water Management in Africa. South Africa: Johannesburg; 2005. Integrated water resource management in Tanzania: interface between formal and informal institutions; p. 26-28.
- Southgate, C.; Hulme, D. Uncommon property: the scramble for wetland in southern Kenya. In: Woodhouse, P.; Bernstein, H.; Hulme, D., editors. *African Enclosures? The Social Dynamics of Wetlands in Drylands*. Trenton, NJ: Africa World Press; 2000. p. 73-117.
- Spencer, P. Becoming Maasai, being in time. In: Spear, T.; Waller, R., editors. *Being Maasai: Ethnicity and Identity in East Africa*. Athens, OH: Ohio University Press; 1993. p. 140-156.
- Stave J, Oba G, Stenseth NC. Temporal changes in woody-plant use and the ekwar indigenous tree management system along the Turkwel River, Kenya. *Environmental Conservation*. 2001; 28(2): 150–159.
- Stave J, Oba G, Bjora CS, Mengistu Z, Nordan I, Stenseth NC. Spatial and temporal woodland patterns along the lower Turkwel River, Kenya. *African Journal of Ecology*. 2003; 41(3):224–236.
- Stave J, Oba G, Nordan I, Stenseth NC. Traditional ecological knowledge of a riverine forest in Turkana, Kenya: implications for research and management. *Biodiversity and Conservation*. 2007; 16(5):1471–1489.

- Tangestani MH. Comparison of EPM and PSIAC models in GIS for erosion and sediment yield assessment in a semi-arid environment: Afzar catchment, Fars Province, Iran. *Journal of Asian Earth Sciences*. 2006; 27(5):585–597.
- Thompson M, Homewood K. Entrepreneurs, elites, and exclusion in Maasailand: trends in wildlife conservation and pastoralist development. *Human Ecology*. 2002; 30(1):107–138.
- Western D. Water availability and its influence on the structure and dynamics of a savanna large mammal community. *East African Wildlife Journal*. 1975; 13:265–286.
- Woida, K.; Clark, KB. A GIS adaptation of PSIAC for predicting sediment-yield rates; Proceedings of the Seventh Federal Interagency Sedimentation Conference; Reno, NV. 2001. p. X-25-X-32.
- Wolman MG. A method of sampling coarse river-bed material. *American Geophysical Union*. 1954; 35(6):951–956.

Fig. 1. Watersheds of the four study rivers and village boundaries. Rivers indicate the location of elevation-derived flow paths and do not necessarily represent active channels.

Fig. 2.
River elevation profiles and sampling sites.

Fig. 3.

Downstream trends in channel dimensions for the four study rivers. Note the different x-axis scales for each river.

Fig. 4.

Bedload particle size associated with 84th, 50th, and 16th percentiles.

Fig. 5.
Proportion of bedload material in each size class.

Kikoti

Loiborsiret

Kiti Engare

Terrat

Contributing area (km²)

Fig. 6.

Proportion of sediment in the 2–4 mm size class as a function of drainage area. Dashed lines indicate the location of villages, road crossings, and main access points; X's indicate the location of substantial changes in bed slope.

○ Kikoti △ Kiti Engare ● Loiborsiret □ Terrat × Scenario

Fig. 7.

Plot of sediment size and sediment discharge of Kiti Engare, Loiborsiret, Terrat, and a hypothetical scenario relative to Kikoti River. The solid line represents no difference in water discharge between locations 1 and 2. Dashed lines indicate differences in water discharge by a factor of two. Points above or to the right of the line would steepen through upstream deposition and points below or to the left would degrade through channel scour. The arrows indicate a hypothetical trajectory of change from one state to another.

Table 1

General characteristics of four study rivers

River	Mean slope angle	Drainage area (km ²)	Flow	Confinement	Floodplain	Use
Kikoti	-0.016	6.0	Ephemeral (during and shortly after rain events)	Low	Moderately well developed; bushland, grassland, and scattered riparian trees downstream	No permanent settlements or development; grazing available; 35–40 actively used hand-dug wells in the channel and floodplain; wildlife present
Kiti Engare	-0.008	631.3	Ephemeral/Intermittent (during and shortly after wet season)	Low-Moderate	Moderately well developed; bushland and open-woodland upstream, scattered riparian trees downstream	Little settlement and development; several hand-dug wells in floodplain and channel; one functional handpump in the floodplain; wildlife present, especially in downstream reaches
Loiborsiret	-0.008	160.9	Intermittent (during and shortly after wet season; sustained pools of water)	Low-Moderate	Moderately well developed; bushland upstream, riparian woodland downstream	Village center near river; road and livestock crossings; 8–10 wells near village in floodplain; 3 hand-pumps; 1 concrete barrier in channel; wildlife present
Terrat	-0.011	124.6	Intermittent (during and shortly after wet season; sustained pools of water)	Low-Moderate	Moderately well developed; bushland upstream, riparian woodland downstream	Village center near river; road and livestock crossings; wells near village and downstream; fewer signs of wildlife

Table 2

Hypothesized geomorphic relationships of the four study rivers

River	Land use change (Rank)	Sediment yield (Rank)	Depth (Rank)	Width (Rank)	Area (Downstream trend)	Bedload sediment (Size)	Sediment size (Downstream trend)
Kikoti	4	4	4	4	Increase	Coarse	Decrease
Kiti Engare	2	3	2	3	No Clear Trend	Fine	Decrease
Loiborsiret	3	2	3	2	No Clear Trend	Fine	Decrease
Terrat	1	1	1	1	Decrease	Fine	Decrease

Table 3

Area (km² in parentheses) and estimated sediment yield (SY; m³/km²) of each land use/land cover type within each river catchment

	Kikoti		Kiti Engare		Loiborsiret		Terrat	
	Area	Mean SY	Area	Mean SY	Area	Mean SY	Area	Mean SY
Rangeland	93.67% (6.00)	134.64	50.54% (336.38)	170.03	71.39% (121.20)	182.76	56.72% (74.62)	235.17
Forest	0.55% (0.04)	65.99	43.54% (289.77)	177.31	26.61% (45.18)	181.54	19.19% (25.25)	317.46
Cultivated	0.65% (0.04)	177.31	3.35% (22.28)	252.38	1.61% (2.73)	193.67	7.11% (9.36)	421.06
Bare	5.13% (0.33)	194.81	2.50% (16.64)	255.36	0.39% (0.65)	476.43	16.97% (22.32)	609.97
Water	0.00% (0.00)	0.00	0.07% (0.45)	0.00	0.00% (0.01)	0.00	0.01% (0.01)	0.00
Total	100% (6.41)		100% (665.51)		100% (169.78)		100% (131.57)	

Table 4Correlation between weighted mean sediment yield (*SY*) and sediment size by river

	Weighted mean <i>SY</i> (m ³ /km ²)	log(<i>D</i> ₈₄)	log(<i>D</i> ₅₀)	log(<i>D</i> ₁₆)
Kikoti	137.62	1.54	0.47	0.12
Kiti Engare	177.98	1.40	0.27	0.09
Loiborsiret	183.73	1.44	0.29	0.09
Terrat	327.75	1.13	0.27	0.09
Pearson correlation		−0.99**	−0.59	−0.55

** Significant at the $p < 0.01$ level.

Table 5

Hypothesized (H) and observed (O) geomorphic relationships of the four study rivers

River	Land use change (Rank)		Sediment yield (Rank)		Depth (Rank)		Width (Rank)		Area (Downstream trend)		Bedload sediment (Size)		Sediment size (Downstream trend)	
	H	O	H	O	H	O	H	O	H	O	H	O	H	O
Kikoti	4	4	4	4	4	3	4	3	Increase	Increase	Coarse	Coarse	Decrease	Decrease
Kiti Engare	2	2	3	3	2	4	3	4	No Clear Trend	Weak Increase	Fine	Fine	Decrease	Weak Decrease
Loiborsiret	3	3	2	2	3	1	2	1	No Clear Trend	No Clear Trend	Fine	Fine	Decrease	No Clear Trend
Terrat	1	1	1	1	1	2	1	2	Decrease	Increase	Fine	Fine	Decrease	Weak Decrease