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Original Research Article

Upstream land-use negatively affects river flow dynamics in the Serengeti National Park

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A B S T R A C T

In the Greater Serengeti-Mara ecosystem, with the Serengeti National Park (SNP) at its core, people and wildlife are strongly dependent on water supply that has a strong seasonal and inter-annual variability. The Mara River, the only perennial river in SNP, and a number of small streams originate from outside SNP before flowing through it. In those watersheds increasing grazing pressure from livestock, deforestation, irrigation and other land uses affect river flows in SNP that subsequently have impacts on wildlife. We quantified the changes since the 1970s of river discharge dynamics. We found that the baseflow recession period for the Mbalageti River has remained unchanged at 70 days, which is a natural system inside SNP. By contrast it has decreased from 100 days in the 1970s to 16 days at present for the Mara River, coinciding with increased commercial-scale irrigation in Kenya that extract Mara River water before it reaches SNP. This irrigation will result in zero flow in the river in SNP if the proposed dams in the river in Kenya are built. We observed high flash floods and prolonged periods of zero flows in streams draining livestock grazed watersheds, where severe major erosion prevails that results in gully formation. This eroded sediment is expected to silt and dry out the scattered dry season water holes in SNP, which are an important source of drinkable water for wildlife during the dry season. It appears likely that the future water supply of SNP is at risk, and this has major consequences for its people and wildlife. Ecohydrology-based solutions at the catchment scale are urgently needed to reduce catchment degradation while ensuring sustainable water provision.

1. Introduction

Semi-arid and savannah ecosystems of East Africa are home to most diverse wildlife communities and important in tourism-driven economy. However, these communities face changes in surface water availability that is predicted to affect their abundance and composition

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(Veldhuis et al. 2019; Kihwele et al. 2020). Surface water connects human-dominated landscape and natural ecosystems, with upstream-downstream effects. Natural ecosystems are capable of sustaining the provision of freshwater to downstream dependants and though the water supply in the dry season may be limited in arid areas, this benefits ecosystem processes and people's livelihoods. In contrast, human activities upstream affect catchment quality through decreased low-flow periods and destruction of flow pathways (Nugroho et al. 2013; Lin et al. 2015; Jacobs et al. 2018; Lee et al. 2018). Such cause-and-effects relationship from declines of river flows have been documented for a number of rivers in East Africa, including the Ruaha River (Mtahiko et al. 2006; Kihwele et al. 2018), the Mara river (Gereta et al. 2009; Mango et al. 2011), the Wami River (Kiwango et al. 2015) and the Katuma River (Elisa et al. 2010). Sustainable supply of water depends on the condition of watersheds, which is driven by human activities (Nugroho et al. 2013; Welde and Gebremariam 2017; Guzha et al. 2018; Jacobs et al. 2018; Lee et al. 2018). Furthermore, the IPCC predicted that climate change in East Africa may affect rainfall and thus river flows with consequences for livelihoods and wildlife. However, the rainfall data from the Masai Mara National Reserve in Kenya, adjoining the Serengeti National Park (SNP), do not support that prediction so far (Bartzke et al. 2018).

In the Serengeti-Mara ecosystem, with SNP at its core (Fig. 1a), land use changes and catchment degradation are the key factors driving the progressive decline of the flows of the Mara River, the only perennial river in SNP (Fig. 1b;Mati et al. 2008; Gereta et al. 2009; Mnaya et al. 2017). Between 1973 and 2000, for the Mara watershed upstream of SNP, there has been a decline in natural forest by 31%, an increase in agricultural land by 204%, and savannah and rangelands reduced from 79% to 52% of the basin land (Mati et al. 2008; Kipampi et al. 2017), and all these have significantly impacted the river flow dynamics. In addition, there is commercial-scale irrigation in Kenya using Mara River water (Fig. 1c); in 2005 it extracted Mara River water at a rate of 0.5 $m^3 s^{-1}$ in the dry season (Hoffman et al., 2011), which is larger than the measured minimum Mara River flow of 0.3 m^3 s^{-1} in SNP in 2005 (Gereta et al. 2009). Thus in 2005 irrigation farmers in Kenya took out about 62% of the Mara River water during the dry season.

Water availability determines habitat use and the seasonal distribution of large herbivores during the dry season (Hopcraft et al. 2012; Owen-Smith 2015). Thus human activities that change water availability is expected to affect large herbivores, particularly water dependent species (Kihwele et al. 2020). The annual animal migration in SNP depends on water from the Mara River in the dry season and several scattered water holes in the other, otherwise dry, rivers in SNP (Wolanski et al. 1999; Mati et al. 2008; Gereta et al. 2009; Mnaya et al. 2017). Hydrologically, the Serengeti-Mara ecosystem is made up of four different watersheds, namely the transboundary Mara River (shared between Kenya and Tanzania), the Grumeti River, the Mbalageti River, and the Simiyu/Duma River in the far southwest of SNP, all flowing westwards to Lake Victoria (Wolanski et al. 1999). Despite of the ecological importance of surface water, the availability of water in the ecosystem has not been monitored, nor has the threat to this water been quantified from the increased use of river water for irrigation, the increased use of fires, and the increased overgrazing by cattle in watersheds originating from upstream SNP but draining into SNP mainly through the Grumeti River. If these flow dynamics are not quantified and monitored, their consequences for people and wildlife cannot be predicted and mitigated.

Thus, we collected field data on the effects of land use regimes on the flow properties of streams draining small watersheds inside and outside SNP, and simultaneously we collected data on rainfall and the flows in the large rivers in SNP. Using these data, we quantified the cause-and effects processes affecting these life supporting components of the ecosystem in SNP. We suggest that these processes are significant enough that they need to be taken into account by decision makers for the sustainable management of SNP and its surrounding areas to ensure sustainable biodiversity conservation and flows of benefits to people. Our study does that by answering four hydrological questions of importance to the ecosystem, namely: (1) What are effects of livestock grazing in the Loliondo Game Controlled Area (LGCA; Fig. 1) outside SNP on the flow characteristics of small streams draining into SNP?; (2) What are the effects of fire inside SNP on the flow characteristics of small streams?; (3) Is the hydrology regime stable inside SNP?; (4) Is the Mara River likely to dry out in SNP in the future due to human activities in Kenya?

2. Material and Methods

2.1. The study area

The study area covered the Serengeti National Park (SNP) and the LGCA. The climate of the area follows the classical bimodal rainfall pattern of East Africa, mainly restricted to November-May, peaking in December and in March/April. The long rain generally occurs from late February through May while short rain occurs between October and December. There is a pronounced rainfall gradient with rainfall increasing from the south-east (500 mm) to the far-north (1200 mm). The altitude varies from 3000 m in the Ngorongoro highlands to about 920 m in the west near the shore of Lake Victoria. The physical boundary of the ecosystem is formed by the Great Rift Valley and the Ngorongoro highlands in the east, and Lake Victoria in the west.

2.2. Study design

We studied the flow dynamics by establishing gauging sites in both large rivers (Fig. 2) and small streams (Fig. 3). The watershed areas of both large rivers and small streams at each gauging site were delineated from digital elevation model (DEM) using hydrology toolset of ARG-GIS 10.4 (ESRI). The DEM data were acquired through Shuttle Radar Topographic Mission (SRTM) of the area downloaded from the United State Geological Survey (USGS) website. Through the hydrology tool of the spatial analyst tool we processed the DEM data by running the flow direction and

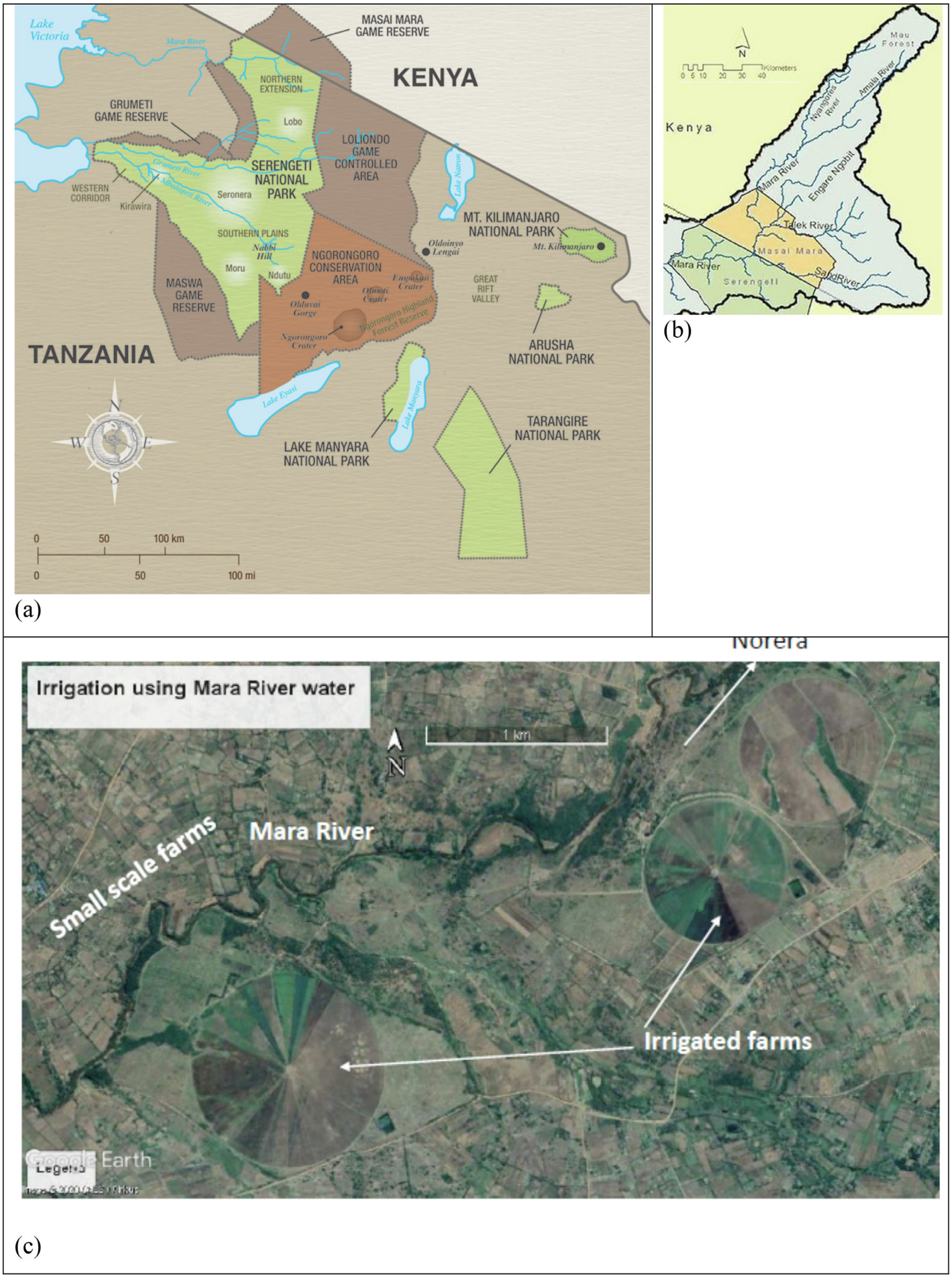

Fig. 1. (a) Map of Serengeti Mara ecosystem showing SNP, its surrounding protected areas and its large rivers. (b) Map of the Mara River watershed in Kenya; the Mara River is formed by the confluence of the perennial Amala and Nyangores Rivers that start in the Mau forest; the Mara River is the only perennial river in the Serengeti Mara ecosystem. (c) GoogleEarth view of one of the two large-scale commercial irrigated farms and the thousands of small artisanal farms in Kenya, all use Mara River water.

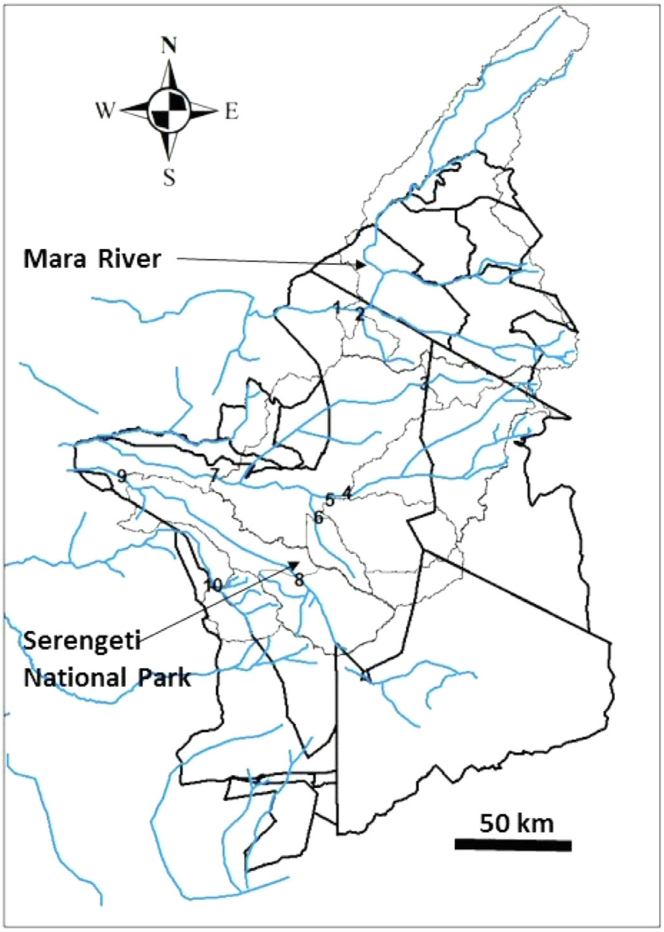

Fig. 2. Map showing the hydrology network of the large rivers (shown in thick blue lines) in SNP. The numbers indicate the gauging sites described in Table 1. The watershed boundaries are shown as thin black lines.

accumulation and established a pour point along a network of channels. Based on the pour points, we delineated 12 small watersheds of 1 km^2 for experimental watersheds and seven sub-watersheds for monitoring flow dynamics in large rivers. These small watersheds are all very close to each other in the same landscape with visual similar features, suggesting that they have similar physical environmental properties such as soil texture, soil heat and water retention properties.

2.3. Rainfall data

We acquired rainfall data for the period 2016 to 2018 from Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS) through the web browser https://www.chc.ucsb.edu/data.

2.4. Measurement of the discharge of large rivers

River flow dynamics in the large rivers were monitored from July 2016 to October 2018 at the stations shown in Fig. 2. The headwaters of the watersheds varied in their land use. The Bologonja, Mbalageti, Seronera and Duma watersheds are natural, entirely protected ecosystems. The headwaters of the Mara, Grumeti, Banagi and Warangi Rivers are located in human-dominated ecosystems upstream of SNP (Figs. 1 and 2). The loggers logged data at 30 min interval. For each of the river, we developed a rating curve from typically 8-10 measurements of the flow rates and the water level following Chaudry (2008):

$$Q = Ch^m \tag{1}$$

where Q is the water discharge ($m^3\ s^{-1}$), C is the discharge when the effective depth of flow h is equal to 1 m, and m is the coefficient that typically has a value between 2 and 4 according to the watershed. We then used the rating curve for each station to calculate the discharge rate for the entire period of observation from the half-hourly collected water level data.

2.5. Measurement of the discharge of the streams draining the small experimental watersheds

To quantify how land use affects the watersheds' hydrological processes, we monitored the streamflows in small (1 km^2) watersheds in SNP subject to fire and wildlife

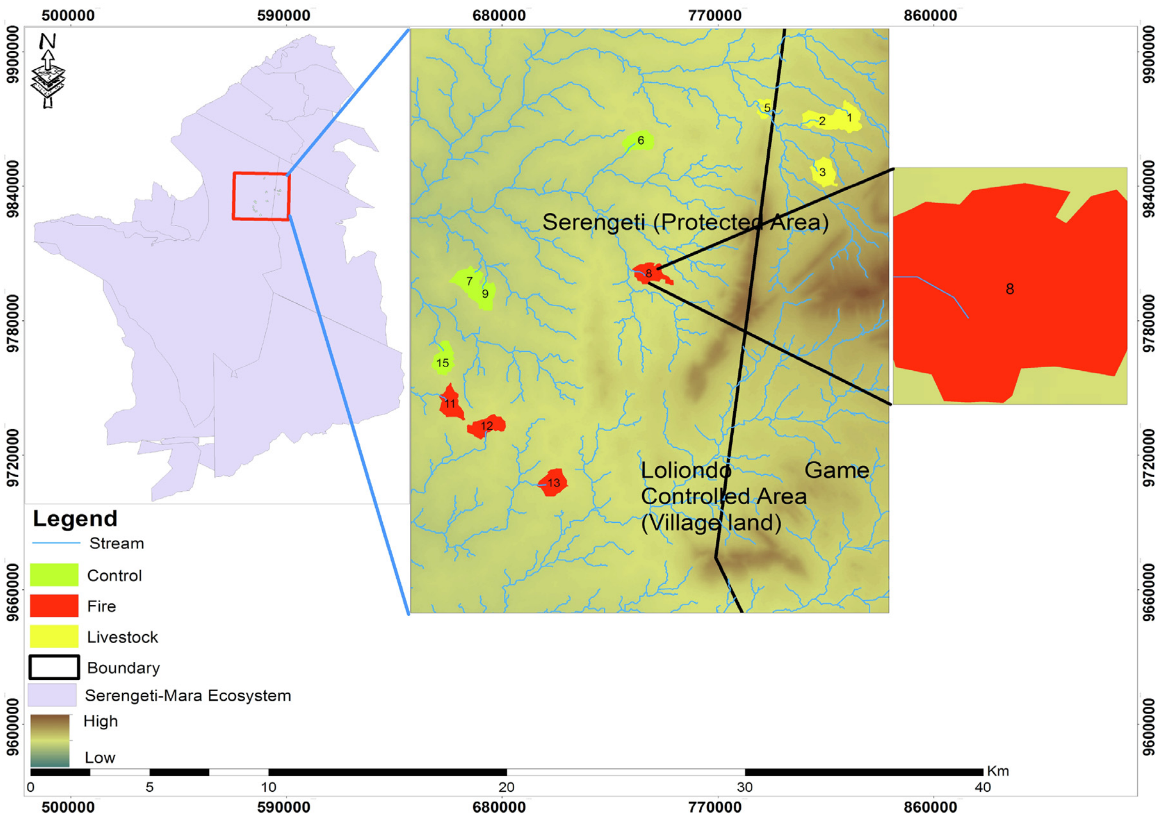

Fig. 3. Location of the small experimental watersheds used for livestock and fire treatment experiments located within Serengeti National Park and Loliondo Game Controlled Area (LGCA). 1-3, 5: Livestock grazing treatment; 6-7, 9, 15: Control treatment with wildlife grazing and no fire; 8, 11-13: wildlife grazing with fire.

grazing (fire), livestock grazing in LGCA (livestock), and wildlife grazing without cattle and fire in SNP (control) (Fig. 3). Data on streamflow were measured by water pressure loggers (ReefNet's third generation dive data loggers Sensus Ultra) from March 2017 to November 2017. The loggers were deployed at the pour point of each delineated watershed to measure the pattern of water levels following rainfall events. The loggers logged data at 15 min interval, so that all flow events were captured. To convert these water level data into discharge data, we used the Manning equation for open channel hydraulics (Chaudry, 2008):

$$Q = VA \tag{2}$$

$$V = (k/n)(A/P)^{2/3}S^{1/2} \tag{3}$$

where Q is the discharge, n is the Manning coefficient that depends on the stream bed sediment and roughness characteristics and vegetation in the stream, A is the cross-sectional area (m^2) of the stream, P is the wetted perimeter (m), S is the slope of the stream, V is the velocity of water ($m\ s^{-1}$) of the flowing water, and k ~ 1. These small watersheds are all very close to each other in the same landscape with visual similar features, suggesting that they have similar physical environmental properties such as soil texture, soil heat and water retention properties.

2.6. Measurement of grass biomass in small watersheds

The grass biomass of each small watershed was measured along three transects perpendicular to the river bank of 200 m length at 0, 100 and 200 meters from the river bank. At each such site, a 20 m sub-transect was laid down where grass biomass was measured by dropping a Rising Plate Meter/Pasture Meter at ten points, 2 m apart, and measuring the grass height as a proxy for grass biomass. The data on grass biomass were analysed in a mixed model analysis of variance, with treatment (livestock grazing, fire, and control) as fixed effects, and transect nested with watershed, and watershed as random effects. The model was fitted using the lme function of the nlme library in R version 4.0.2 (R Core Team 2020) as lme(Biomass~Treatment*Distance,random=~1|Watershed/Transect, method="REML",data=data.grass). The significance of the differences between the treatments was calculated using a Tukey HSD test, using the transect-average biomass as replication.

2.7. Measurement of the infiltration rate in small watersheds

Data on infiltration rate were obtained using a single ring infiltrometer (15 cm diameter). In each experimental

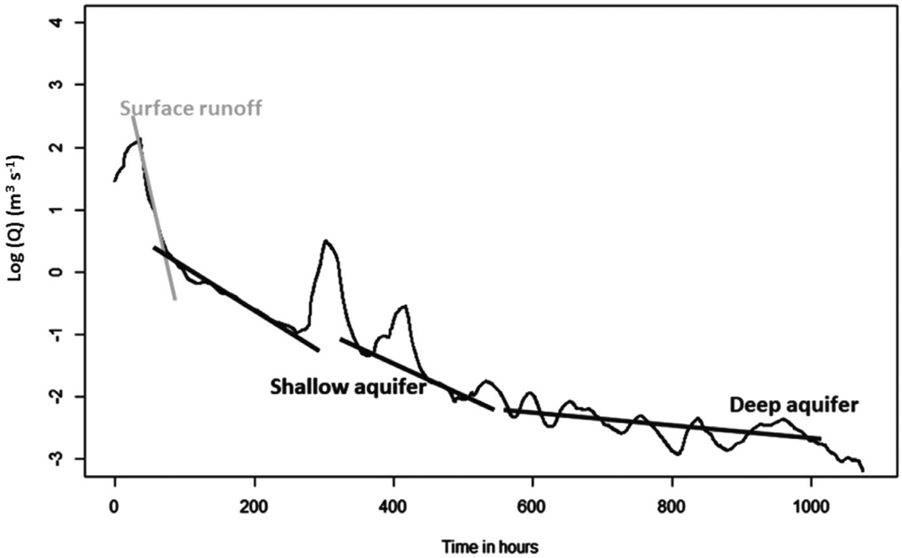

Fig. 4. Recession curve for the discharge after rainfall of the Seronera River (site 6 in Fig. 2) in SNP from our data, showing the method used to estimate the flow recession time scale. This method was used for both large rivers and small streams.

watershed, we installed the infiltrometer by driving it about eight centimetres into the soil. We then filled the ring with water. We monitored the infiltration of water into the soil by manually recording the depth of the water in the infiltrometer every 5 min for an hour. We calculated the average infiltration rate for each infiltration sequence as the slope of the linear regression of the remaining water level versus time. Visual inspection of the infiltration graphs showed that a linear model was appropriate. We then tested the effect of treatment (livestock grazing, fire, and control) using one-way analysis of variance, followed by Tukey contrasts.

2.8. Estimating the recession time scale for both large rivers and small streams

The large rivers and the small stream in SNP and LGCA have a classical hydrological behaviour at recession, comprising of an exponential decrease of surface runoff after rain, followed by a slower exponential decrease of the flow sustained by the drainage of the shallow aquifer, and finally followed by an even slower exponential decrease of the flow sustained by the drainage of the deep aquifer (Brown et al. 1981). An example from our data for the Seronera River is shown in Fig. 4. Thus we could estimate the baseflow recession time scale, which is the time required for the base flow to decrease to 1.8% of its original value, by using Eq. (4):

$$Q = Q_o \exp(-kt) \quad (4)$$

where t is the time in days, k is the recession coefficient (it has units of day^{-1}; it is the slope of the flow recession curve in a log plot), Q is the discharge (m^3 s^{-1}) and Q_o is the discharge at time 0 after rainfall.

Table 1
Large river gauging stations, river name and measurement site.

Gauging station	River name and measurement site
1	Mara River at Kogatende
2	Bologonja River at Makutano bridge
3	Grumeti River at Klein's bridge
4	Warangi River at Mbuzi mawe bridge
5	Banagi River at Banagi bridge
6	Seronera River at Morcas bridge
7	Grumeti River at Dala bridge
8	Mbalageti River at Sopa bridge
9	Mbalageti River at Handajega bridge
10	Duma River at Duma ranger post/Duma bridge

3. Results

3.1. Visual observations

The rivers with headwaters entirely within SNP generally showed no sign of bank erosion as their banks were covered by vegetation (Figs. 5a-c). The streams originating from intensively cattle-grazed areas outside of SNP in Loliondo Game Controlled Area (LGCA) were mostly erosion gullies with intense erosion during high flows (Fig. 5d) and this gully formation propagated downstream in SNP (Fig. 5e).

3.2. Flow characteristics of streams in small watersheds

The flows in the small streams draining watersheds originating from cattle-treated areas in LGCA varied rapidly with short-lived flash floods and flow recessions lasting a few hours only (Fig. 6, Table 2). By contrast the flows in the small streams draining the fire-treated and the control watersheds were less 'spikey' with smaller floods and with flows lasting much longer after rainfall. Indeed, the

Fig. 5. Pictures illustrating the contrast between the stable river banks facilitated by stabilising vegetation within SNP (a: Warangi River; b: Mbalageti River; c: Seronera River), (d) a stream degrading into a gully in the cattle-overgrazed LGCA just outside SNP, and (d) an eroding stream in SNP affected by cattle in LGCA.

Table 2
The baseflow recession time scales (days) of stream draining 12 small watersheds treated with livestock grazing, fire, and control.

Watershed number	Treatment	Recession time scale (days)
1	Livestock grazing	0.15
2	Livestock grazing	0.08
3	Livestock grazing	1.68
5	Livestock grazing	0.02
6	Control	6.65
7	Control	2.97
9	Control	0.54
15	Control	1.97
8	Fire	1.35
11	Fire	3.62
12	Fire	1.00
13	Fire	3.88

mean flow recession period in the control watersheds was 2.53 days (±1.72, n=4), which is not significantly different from that (2.46 days; ±1.49, n=4) in the fire treated watersheds, and this is significantly larger than that of 0.106 days, (±0.066, n=4) in the livestock treated watersheds. As a result, the streams in the control small watersheds had no flow for 63.98 % (±16.83, n=4) of the time on the average, in the fire treated small watersheds for 73.70 % (±5.12; n=4) of the time, and in the livestock treated small watersheds for 83.98 % (±9.13, n=4) of the time (Fig. 6).

3.3. *Grass biomass and infiltration rate in the experimental watersheds*

The mixed model analysis of variance for the grass biomass showed a significant effect of treatment ($F_{2,12}$=4.23, P<0.041) and distance ($F_{1,2652}$=18.22, P<0.001), while their interaction was not significant ($F_{1,2652}$=2.36, P=0.09). A subsequent Tukey HSD test showed that the grass biomass was not significantly different between control and fire treated watersheds (P>0.05) while the watersheds with livestock present had a significantly lower biomass than both these treatments (Fig. 7). In general, there was inter-specific variation in grass biomass within and between watersheds with similar treatments (Fig. S_1).

The infiltration rate data suggest that the control watersheds had higher infiltration rates than the fire and livestock grazing treatment (Fig. 8), but this treatment effect was not significant in a one-way ANOVA ($F_{2,12}$=2.08, P=0.17).

3.4. *Flow characteristics of large rivers*

The large rivers within SNP each had different flow recession rate, so that some rivers had longer-lasting flows than others, but nevertheless the flows all varied slowly with time scales of days to weeks (Fig. 9a-c, Table 3). The discharges varied from river to river, and so did the water yield (i.e. the discharge divided by the watershed area) and this can be attributed not just to the geology but also to the rainfall that varied spatially (Fig. 9d-f). The mean baseflow recession time scale was 27.63 days (±23.3, n=8). Most importantly for the ecology, excepting the Mara River, which is perennial, and the Bolongonja River, which is sustained by a perennial spring with the small flow of ~ 0.02 m^3s^{-1}, all the other rivers dried out during the dry season. The average number of days with zero flow in each river was 67.1 days per year (±44, n=5; Minimum=3.5

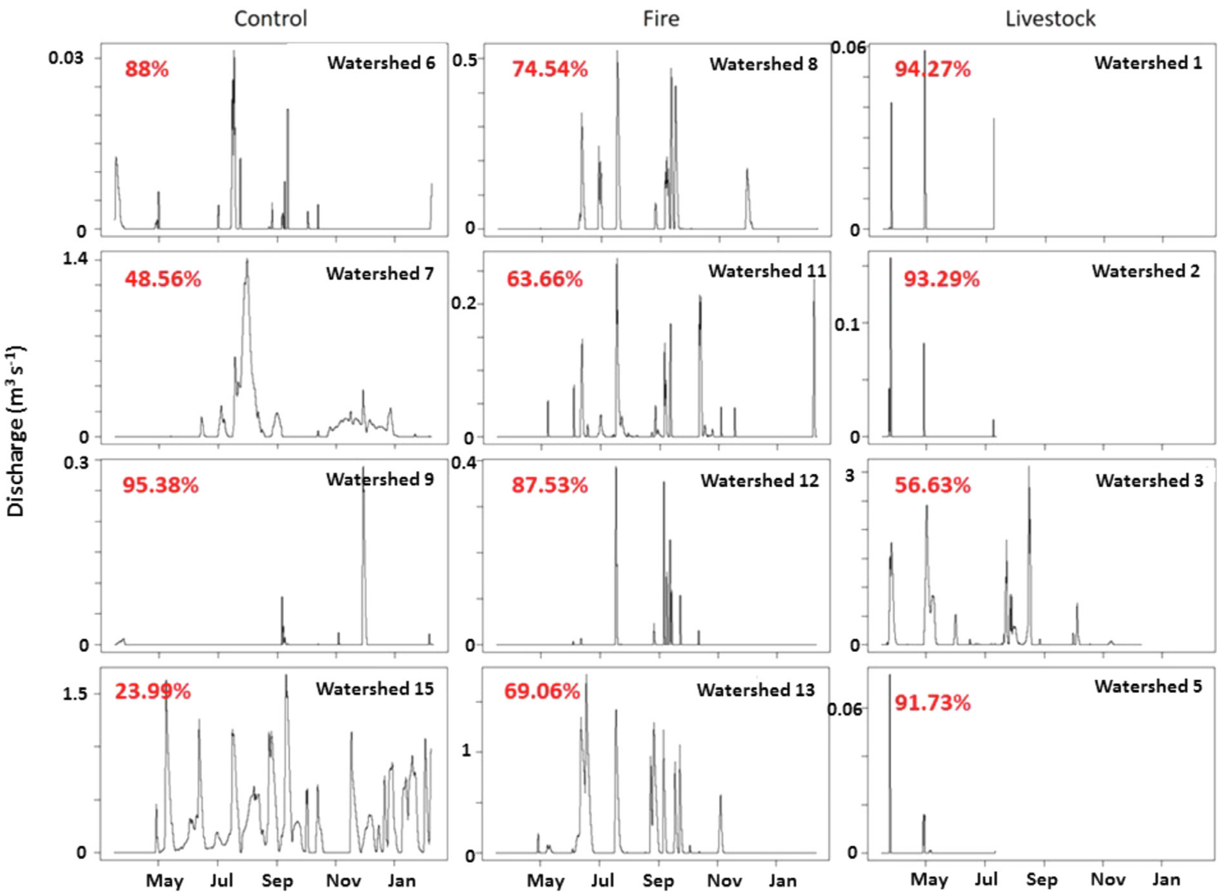

Fig. 6. Time-series plot of the discharge in the small streams draining the 12 experimental watersheds, 4 in each treatment. Left column: 4 watersheds located in SNP used as control that were only grazed by wildlife with no fire; Middle column: 4 watersheds subjected to intensive livestock grazing in LGCA; Right column: 4 watersheds subjected to fire and wildlife grazing inside SNP. The numbers in red bold are the percentage of the time that the stream had no flow.

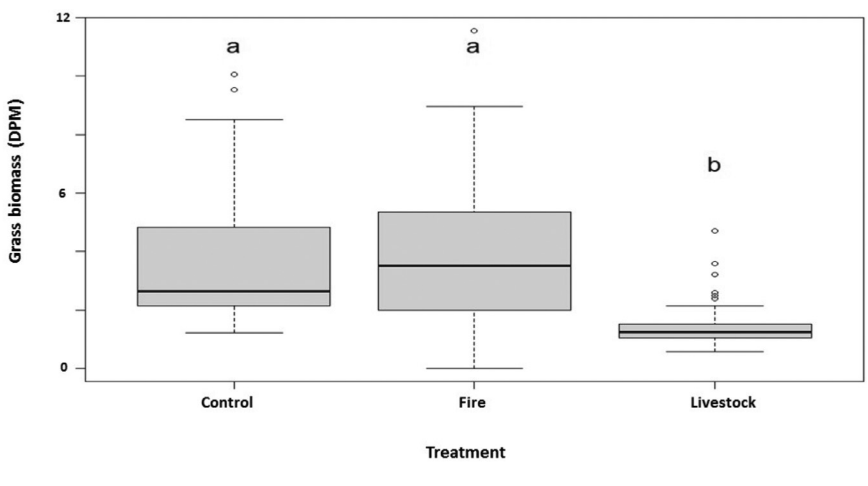

Fig. 7. Variation of the grass biomass (indexed as Disc Pasture Meter [DPM] settling height; mean ± SE) in the experimental watersheds as a function of the three treatments, shown as boxplots. Means with the same letter are not significantly different (Tukex HSD test after mixed-model analysis of variance, with transect and watershed as random effects).

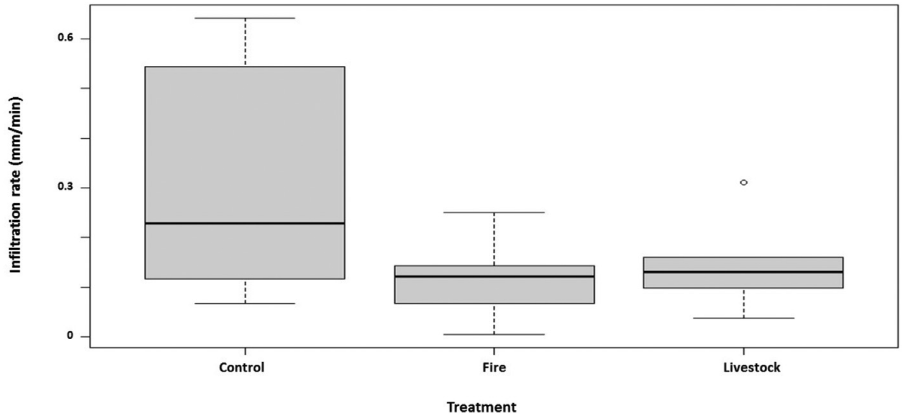

Fig. 8. Variation in the infiltration rate in the experimental watersheds as a function of the three treatments, shown as boxplots. The effect of treatment was not significant ($P>0.05$).

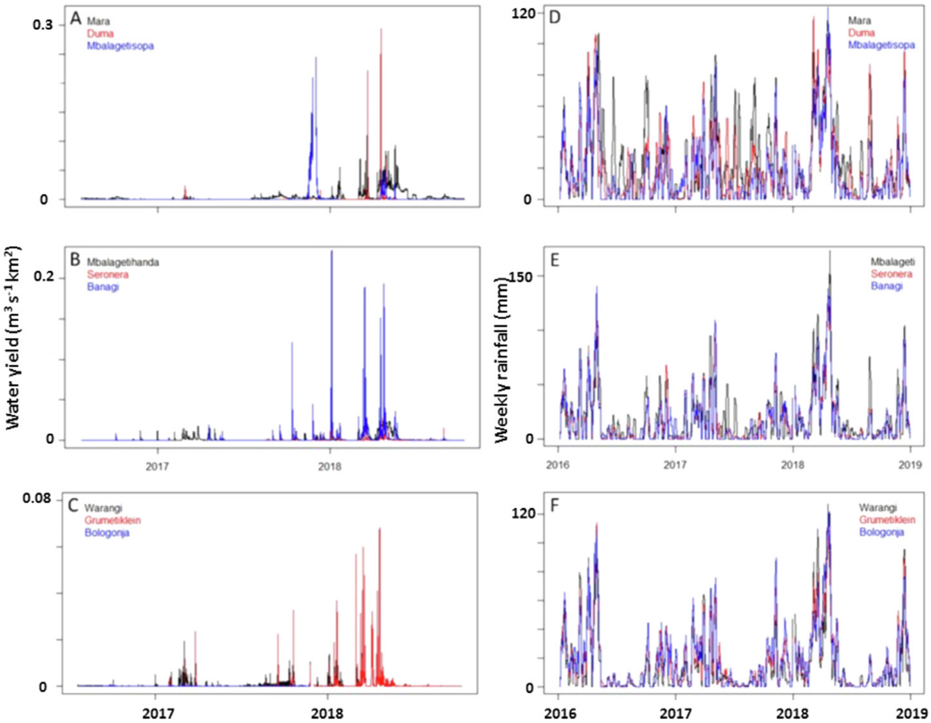

Fig. 9. Time-series plot of (a-c) the daily water yield of the large rivers and (d-f) the weekly rainfall over their watersheds.

Table 3
Comparative recession time scales for discharge levels in river in the 1970-1974 study of SMEC (1977) and Brown et al. (1981) and this study (2016- 2018). Also shown are, for this study period, the maximum, minimum and mean discharge and the number of days with zero flow.

Gauging station no.	Watershed area (km^2)	Recession time scale (days) in 1970-1974	Recession time scale (days) in 2016-2018	Maximum discharge (m^3 s^{-1})	Minimum discharge (m^3 s^{-1})	Mean discharge (m^3 s^{-1})	Number of days with zero flow
1	8,881	100	16.4	623.3	0.1	41.5	0
5	1,423		38.5	132.3	0	2.6	94.5
3	467.5		5.4	11.6	0	0.2	na
6	447.1		29.2	10.4	0	0.4	3.5
2	295.9		8	0.17	0.01	0.02	0
8	1,341	70	70	193.8	0	2.24	na
4	2,492		47.6	27.7	0	1.3	70.9
9	2,810			63.1	0	4.4	130
10	735.		6	147.	0	0.4	36.6

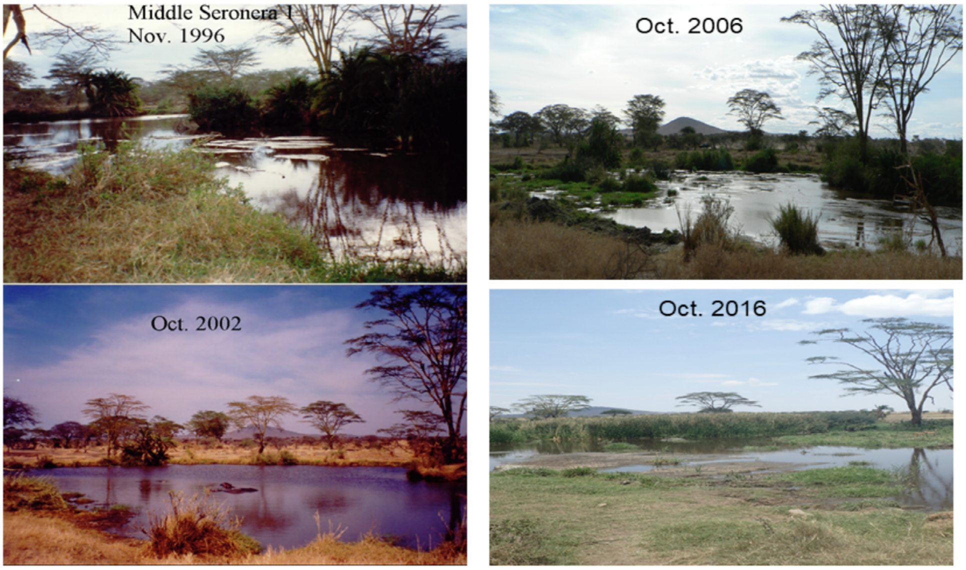

Fig. 10. Sequential photographs from 1996 to 2016, in the dry season, of the same waterhole in the Seronera River. The water hole is silting and this affects the dry season water availability for wildlife.

days; maximum=130 days). Substantial differences in the flow recession time scale occurred between rivers, that time scale ranging between a maximum of 70 days for the Mbalageti River at Sopa bridge and a minimum of 5.4 days for the Grumeti River at Klein's bridge (Table 3). This implies that after rain, the rivers differed significantly in the way their base flows decreased exponentially to 1.8% of the original flow (Fig. 9a-c). The peak recorded discharge (i.e. during floods) for the Mara and Mbalageti rivers was, respectively, 623.3 m^3 s^{-1} on 17 April 2018 and 193.8 m^3 s^{-1} on 2 December 2017 (Fig. S_2). However, these high flow data are based on an extrapolation of the rating curve to levels for which no data exist; hence these data during floods are indicative only. The peak observed flood flows for the Bologonja. Warangi, Grumeti, Banagi and Seronera rivers were, respectively, 0.17 m^3 s^{-1} on 28 March 2017; 27.7 m^3 s^{-1} on 16 March 2018; 11.6 m^3 s^{-1} on 20 April 2018; 132.3 m^3 s^{-1} on 5 January 2018; and 10.4 m^3 s^{-1} on 27 April 2018 (Fig. S_2).

3.5. Historical changes to river flows

The World Meteorological study of the White Nile basin in 1970-1974 gauged the Mara River at Mara Mines and the Mbalageti River near its outlet in Lake Victoria (SMEC, 1977; Brown et al., 1981). Both of these historical gauging sites are very close to our gauging sites. The Mbalageti River watershed is entirely within SNP, thus in a natural state. The Mara River watershed is mostly in Kenya with extensive deforestation and increasing use of Mara River for irrigation occurring in Kenya since the 1970s. As shown in Table 3, the baseflow recession time scale of the Mbalageti River was 70 days in the 1970s and this has not changed, i.e. the hydrological characteristics have not changed in SNP. By comparison the baseflow recession time scale of the Mara River has decreased by a factor of about 6 from 100 days in the 1970s to 16.4 days at present.

3.6. Sedimentation-induced historical changes to rivers inside SNP

The Seronera River (site number 6 in Fig. 2) is located entirely inside SNP and it is now being modified by long-term sedimentation that likely results from wet-season erosion from dirt roads in the southern grasslands of SNP. This is illustrated by sequential photos dating back to 1996 (Fig. 10).

4. Discussion

4.1. Cattle grazing

We investigated how livestock grazing and fire affect the condition of small watersheds and their streamflow yields. The livestock grazing treated watersheds in LGCA had a smaller grass biomass and a smaller water infiltration rate than that in the control watersheds in SNP. The flow recession period was the same (~2.53 days) in the control watersheds and in the fire treated watersheds. However, the flow recession period was much shorter (~0.11 days) in the livestock grazing treated watersheds where, therefore, flash floods were common during rainfall and the flows were short-lived after rainfall. In addition, our visual field observations and photographic evidence revealed intense gully erosion in the small streams originating outside SNP in the LGCA where there is intensive livestock grazing, a clear indication of deteriorating watersheds. These small streams are the tributaries of large rivers of SNP, such as the Grumeti River, which is seasonal. In the dry season these rivers do not flow but they hold water through a network of water holes along the river. The spikey floods in the small streams in LGCA bring this sediment to SNP and this sediment silts these water holes and shortens the time that these water holes retain water in the dry season. Evidence for the silting of water holes from soil erosion upstream is found in water holes in the Seronera River that are silting from erosion from dirt roads in the southern grasslands of SNP. The sedimentation of the dry season water holes is expected to have a severe impact on the ecosystem because water from these water holes allows for spatial niche partitioning and co-existence of diverse grazing herbivores in the dry season (Kihwele et al., in prep.). Thus, cattle grazing in the buffer zones, especially the LGCA, is likely to dry out these water holes in the future and thus this will alter the whole ecosystem processes and functioning. In summary, the hydrology has remained stable for watersheds within SNP but river flows have become much more 'spikey' and fast drying for the watersheds outside SNP but draining into SNP.

4.2. Irrigation in Kenya

The baseflow recession period of the Mbalageti River has not changed (= 70 days; Table 3) since the 1970s. Its watershed is entirely within SNP, thus it is in a natural state because of total protection of resources in SNP. Thus the hydrology of rivers entirely within SNP appears stable over the last 45 years.

By contrast, the baseflow recession time scale of the Mara River in SNP has decreased from 100 days in the early 1970s to 16.4 days at present. This change means that for Mara River water to reach SNP, in the early 1970s in the dry season a rainfall event was needed every 3-4 months in the Mau forest in Kenya, now this is needed every 2-3 weeks. This suggests that a future drought is likely to stop the Mara River flow entering SNP. The main reason for that appears to be commercial irrigation in Kenya. Indeed, Google-Earth images show that there are two commercial-scale irrigation areas using Mara River water in Kenya; one area is that shown in Fig. 1c and it appears slightly changed in surface area since 2005; the other area is located a few km downstream and it appears to have substantially grown by 40 % since 2005, indicating that the total irrigation area may have increased by about 20 %. In 2005 the water extracted from the Mara River for commercial scale irrigation in Kenya was ~ 0.5 m^3s^{-1} during the dry season (Hoffman et al., 2011). In the same year the low flow discharge of the Mara River in SNP was 0.3 m^3s^{-1} (Gereta et al. 2009), implying that in 2005 the commercial irrigators were withdrawing 62% of Mara River water before it reached the Serengeti-Mara ecosystem. In November 2016 we measured a Mara River discharge of 0.16 m^3s^{-1}, i.e. the commercial irrigators in Kenya were extracting ~ 75-79 % of the Mara River water before it reached SNP.

The threat of Kenya withdrawing water from the Serengeti ecosystem is even worse because there are proposed dams on the Mara River and its tributary, the Nyangores River, also in Kenya, as well as a proposal for a dam in the Mau forest in Kenya to divert Amala River water to another watershed to the east; all these dams are located upstream of the irrigation areas. The minimum proposed flow at the outlet of the dams would be 0.1 m^3 s^{-1} (Mnaya et al. 2017). However, the irrigators in Kenya are located downstream of these dams and to maintain their crops they need to extract all that water and thus they will completely dry out the Mara River. This will likely destroy the annual migration of wildebeest and zebras for which SNP is famous (Mnaya et al. 2017). The ecosystem may then change to one supporting a population of resident animals, with no annual migration, around water holes in rivers, at least those that are not silting from overgrazing in LGCA (Mnaya et al. 2011; Weeber et al. 2020). Indeed, there is no other sufficient source of freshwater beside the Mara River in SNP in the dry season because, as shown in Table 3, all the other rivers dry out in the dry season except for the very small flow of ~ 0.014 m^3s^{-1} in the Bologonja River that is fed by a perennial spring. There is no drinkable water either in the southern plains of SNP in the dry season because of high salinity levels (Gereta and Wolanski 1998; Wolanski et al. 1999; Gereta et al. 2009).

This paper is a plea for a strict control of commercial and artisanal irrigation in Kenya and for improved livestock husbandry through increasing control of grazing in watersheds draining into SNP, with urgent action needed in LGCA. Furthermore, the use of fire as a management tool needs to proceed with caution and careful monitoring. Ecohydrology-based solutions are urgently needed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

Authors state that the research was conducted according to ethical standards.

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