Water Science & Technology—WST | 61.4 | 2010

Temporal variability of two contrasting transient pollution events in a pastoral stream

P. T. Yillia, N. Kreuzinger and K. K. Mwetu

ABSTRACT

Two transient pollution events were monitored in a pastoral stream in southwestern Kenya to evaluate their relative contribution to diffuse pollution. Peak loads of pollutants during storm-induced transients were within 3–4 orders of magnitude higher than the short-lived (30–60 minutes) diurnal episodes provoked by in-stream activities of people and livestock. Transient yields were striking during storm-induced events; 778,000, 8,400, 550 and 100 kg day^{-1} for suspended solids, BOD_5, total P and total N, respectively, compared to wet weather base flow (150, 30, 0.8 and 1.4 kg day^{-1}, for the same parameters, respectively). Two forms of concentration-discharge relationships were observed: increases in concentration for turbidity, suspended solids, BOD_5, total P and the faecal indicator bacteria at the peak of the stream hydrograph, and concurrent decreases in concentration for conductivity and total N. Following each storm-induced transient event, a marked improvement in water quality was observed within 48–72 hrs of the receding limb of the stream hydrograph before the next base low was established. It was concluded that storm-induced transients are exceedingly important for the mobilization of pollutants from diffuse sources but both transient events affect stream-channel processes, especially water quality, with the possibility of attendant consequences on the health of riparian inhabitants.

Key words | diffuse pollution, in-stream activities, rainstorm, stream hydrograph, transient events

P. T. Yillia (corresponding author)
N. Kreuzinger
Vienna University of Technology,
Institute for Water Quality,
Resources and Waste Management,
Karlsplatz 13/226,
Vienna,
Austria
E-mail: *pyillia@iwag.tuwien.ac.at*;
norbkreu@iwag.tuwien.ac.at

K. K. Mwetu
University of Natural Resources & Applied Life Sciences,
Institute of Hydraulics and Rural Water Management,
Muthgasse 18,
A-1190, Vienna,
Austria
E-mail: *kmwetu@yahoo.com*

INTRODUCTION

Transient pollution events are episodic water quality fluctuations that occur occasionally above the average temporal variations of pollutants observed in streams. They may be driven by natural phenomena like sporadic rainstorms or regular human induced perturbations such as recreational activities or the accidental spillage of pollutants (Jacobsen *et al.* 1996; Schreiber *et al.* 2001). Transients are detected more frequently in small streams than in large rivers but they can occur on all spatial scales from small plots and watersheds to large drainage basins (Schreiber *et al.* 1996). Depending on the type of land use in the surrounding area and the forces that generate them, large quantities of pollutants can be produced and transported downstream (Schreiber *et al.* 2001).

doi: 10.2166/wst.2010.566

Transients provide an exceptional opportunity to evaluate the magnitude and dynamics of diffuse pollution in pastoral catchments. Most studies of transients try to capture sporadic pollution events that are usually not included in routine evaluation of diffuse pollution. However, transients are difficult to monitor because they are generally short-lived and could pass easily unnoticed. This makes hysteresis in the concentration-discharge relationship difficult to observe (Beck *et al.* 1991; Beck 1996*a*,*b*; Schreiber *et al.* 2001). Nevertheless, data loggers equipped with water quality sensors have been used for continuous online monitoring, in particular, for low frequency events that are typically ignored during weekly/monthly spaced sampling schedules (Whitefield & Wade 1992, 1996; Bowes *et al.* 2005).

Sediment and nutrient mobilization through transient events could be high in the Njoro River Catchment (NRC), a pastoral region in southwestern Kenya. Transients may be responsible for the transport of large quantities of suspended solids, nutrients and degradable organic matter that are derived from land use activities in the catchment. Transients affect stream flow, with possible consequences on the chemical and ecological processes within the stream and the receiving lake–Lake Nakuru, a Ramsar site and a famous tourist destination for wildlife (Mathooko 2001; Mokaya *et al.* 2004; M'Erimba *et al.* 2006; Kibichii *et al.* 2007). There is also the potential for a resultant effect on the health and livelihoods of the riparian inhabitants as water levels fall and pollution levels rise (Yillia *et al.* 2008*a*, 2009). But exactly how much of that pollution is contributed by transient events is not known even though this knowledge is useful for addressing diffuse pollution, which is currently a major concern in the catchment.

The objective of this study was to monitor the temporal variability of diffuse pollution in the NRC and evaluate the relative contribution of storm-induced transient events and the diurnal episodes provoked by the in-stream activities of people and livestock.

MATERIALS AND METHODS

The study stream—Njoro river

Njoro River (60 km) originates from the Mau Hills at 2,800 m (a.s.l) and flows northwards until it joins the main tributary, Little Shuru, at almost midway. After the confluence, the stream follows a north-east course flowing through farmland and settlements, including Nessuit, Egerton and Njoro Town (Figure 1). It turns southwards at the lower reaches through parts of Nakuru Municipality before discharging intermittently into Lake Nakuru at 1,700 m (a.s.l) on the floor of the East African Rift Valley. The geology of this region is characterized by Quaternary volcanic activity. The soils are mainly haplic Phaeozem and well drained, with weakly to moderately developed subangular blocky structure (Owino *et al.* 2006). Wet season occurs in May through September (long wet season) and November through December (short wet season). Generally, both periods are characterized by precipitation events, surface runoff and erosion even though dry spells could occur. The main dry season is in January through April, with a short dry spell between the two wet periods in either September or October.

Transient monitoring site—Turkana flats

A disturbed pool at Turkana Flats was chosen for the transient study (Figure 1). It was ideal for the study due to its location. The pool is situated at the middle polluted reaches and the surrounding area is dominated by farmland and residential plots. It is visited frequently by people and livestock and various in-stream activities are undertaken during visits (Yillia *et al.* 2008*a*). The stream drains approximately 43% of the total catchment area at Turkana Flats with no point source input from wastewater treatment plant (WTP) outfalls upstream. Actually, the closest WTP outfall was situated approximately 500 m downstream (this was the outfall of the wastewater stabilization ponds at Egerton University). Table 1 provides additional information on the NRC and the transient monitoring site–Turkana Flats.

Sampling and analysis

Sampling for transient episodes caused by in-stream activities was undertaken on two successive days at 6 hrs intervals (6 a.m.; 12 midday; 6 p.m. & 12 midnight) during dry season (January–April) in 2006. The schedule was repeated four times and on each sampling occasion, samples were collected <10 m upstream and downstream of activities. Alternatively, four storm events were sampled at peak flow to monitor storm-induced transient events; three samples during long wet season (May–September) and one sample in short wet season (November–December). Three additional samples were taken at 24 hrs intervals after each storm-induced event. The water level of the stream was monitored at Egerton Gate Bridge (<100 m downstream of Turkana Flats) at 3 hrs interval following rainstorm to ascertain the peak of the stream hydrograph during storm events. Using the velocity-area method (UNEP/WHO 1996), stream flow was estimated: (i) at

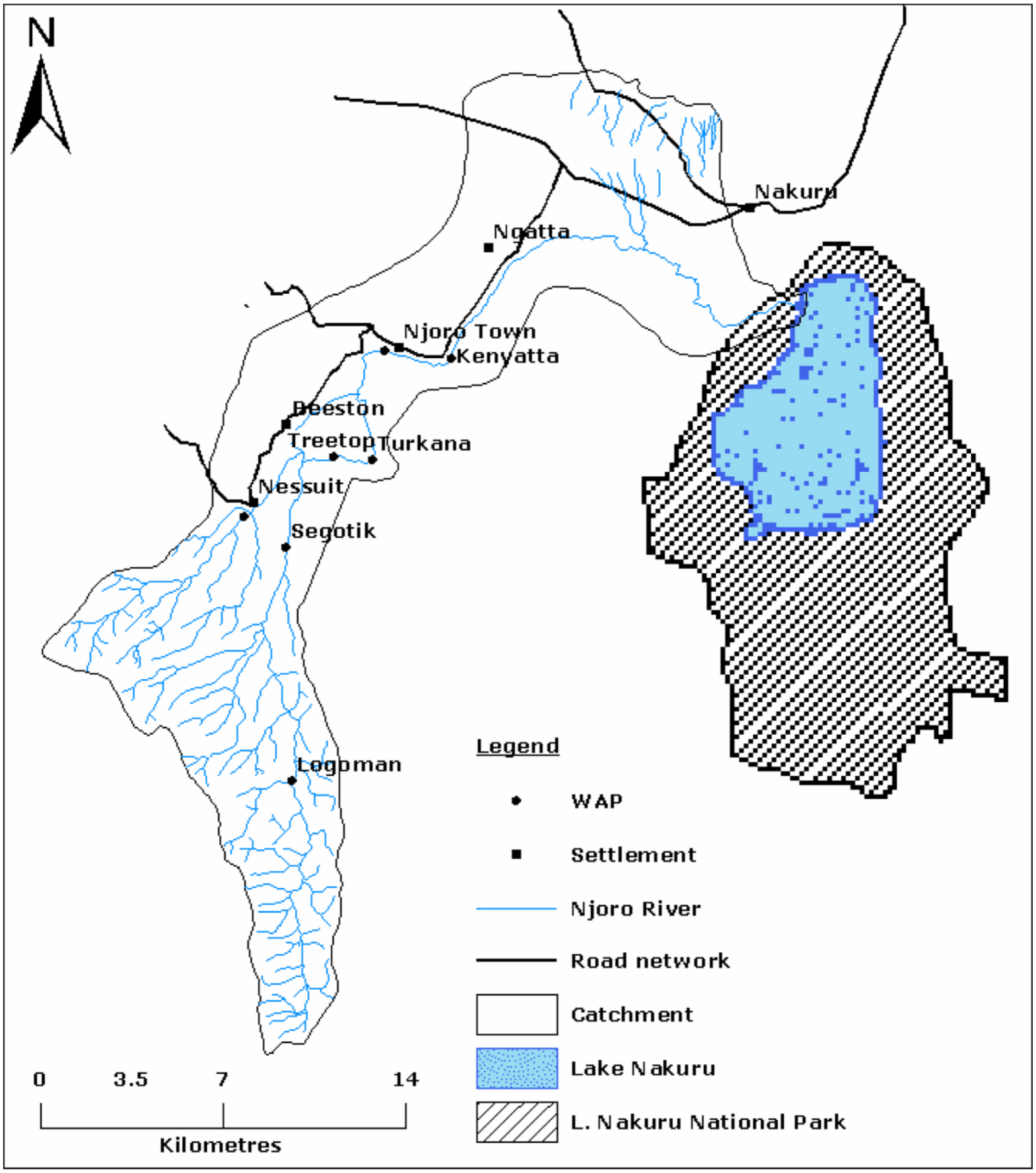

Figure 1 | Njoro River Catchment with settlements and Turkana Flats (the transient monitoring site).

peak water level during storm-induced flow; (ii) during sampling for in-stream activities; and (iii) at two weeks intervals during base flow conditions. Standard analytical procedures were followed to determine suspended solids, turbidity, BOD_5, PO_4-P, NH_4-N, NO_3-N, total phosphorus (P) and total nitrogen (N) (APHA 1995). The specific analytical options that were used have been described previously (Yillia *et al.* 2008*a*,*b*, 2009). The standard membrane filtration technique was used for faecal indicator bacteria (FIB) i.e. Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) (Yillia *et al.* 2008*b*, 2009). Loads of pollutants were estimated from the instantaneous stream flow and the concentration of pollutants (Yillia & Kreuzinger 2009). Additional water

Table 1 | Supplementary data on the Njoro River Catchment and the study site (Turkana Flats)

Stream length	60 km	Arable land	80%
Total drainage area	280 km^2	Forest/woodland	12%
Drainage area at Turkana Flats (TF)	120 km^2	Residential area	6%
TF–kilometres from stream mouth	28 km	Riparian population	70,000
Average hill slopes (upper catchment)	7–27%	Pop. density (upper catchmeent)	$<50/km^2$
Average hill Slopes (lower catchment)	$<4\%$	Pop. density (lower catchmeent)	$>2{,}000/km^2$
Annual rainfall (range since 1944)	600–1,700 mm yr^{-1}	Temperature	9–24°C

quality data was acquired from the results of a parallel weekly monitoring programme at Turkana Flats during the study period. Data analysis was performed with the Statistical Package for Social Sciences (SPSS).

RESULTS AND DISCUSSION

Precipitation and the response of the stream hydrograph

The estimated 30-year moving average of the annual total precipitation for the catchment for the period 1944–2006 is approximately 1,000 mm yr^{-1}, with a wide range (600–1,700 mm yr^{-1}) of variability between dry and wet years. Precipitation is mostly in the form of rain except for some occasional hailstorms. Normally most of the rainfall occurs in May through September (long wet season). But in 2006, a large proportion (46%) of the annual total precipitation (1,135 mm yr^{-1}) happened during the short wet season in November and December, with 302 mm and 219 mm of rainfall, respectively (Figure 2). This was 2–3 times above the monthly average for 2006 (95 mm $month^{-1}$) but within the range of monthly averages (50–110 mm $month^{-1}$) of previous years. Consequently, the annual total precipitation in 2006 was still within the estimated 30-year moving average even though rainfall during the long wet season that year was relatively scanty. Clearly, the annual and seasonal cycle of rainfall is highly

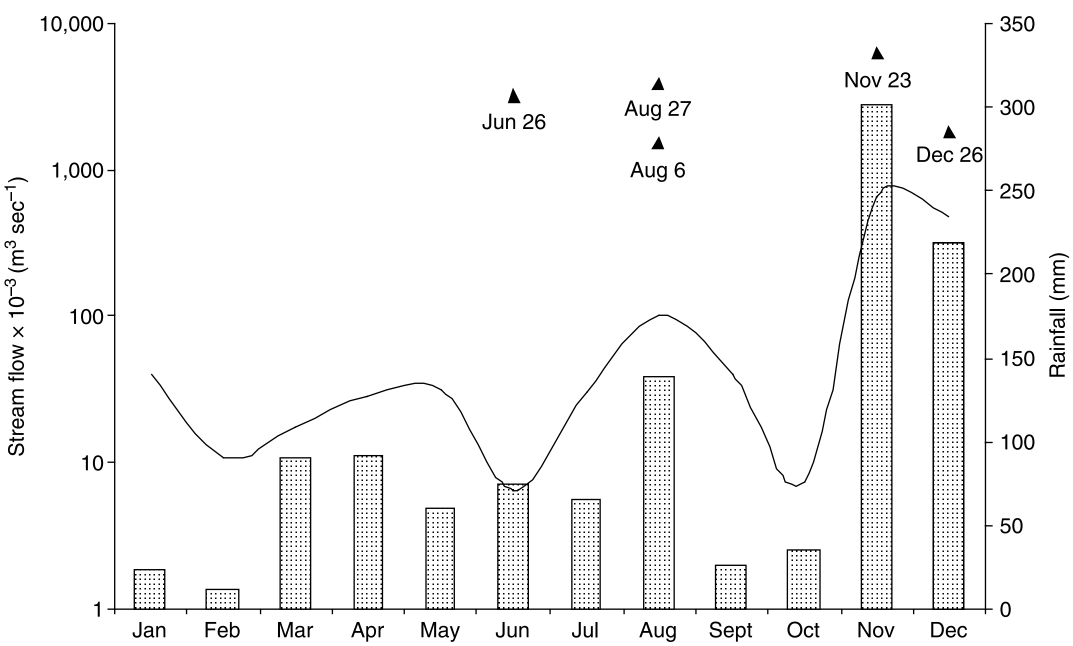

Figure 2 | Mean monthly stream flow (line, on log scale) at Egerton Gate Bridge in 2006 excluding transient flow estimates (triangles, also on log scale) plus the average monthly rainfall (bars) at a weather station nearby (Station No. 09035092 at Egerton University).

variable, with the long-term annual rainfall distribution showing peaks in May, August and November (Mathooko & Kariuki 2000). This temporal pattern of rainfall accounts for the high annual and seasonal variability in the Njoro River flow. The mean monthly stream flow at Egerton Gate Bridge for 2006 is shown in Figure 2. The hydrograph displayed five transient flow events during wet weather. Compared to base flow, the events were characterized by a dramatic increase in stream flow. Runoff accounted for approximately 70–80% of flow at the peak of the ascending limb of the stream hydrograph following rainstorm. The contribution of storm water is easily manifested during rainstorms as the stream is an event-response system. This is largely the product of the intensity and duration of the inciting storm (Table 2). Short-duration rainstorms (1–3 hours) produced short-lived transients with the stream reaching peak flow in less than 30 minutes. Alternatively the stream required 1–2 hrs to reach peak flow during long-duration storms (4–6 hours). However, the resultant transients generated by the latter produced superior peaks with the descending limb of the stream hydrograph lasting much longer (72–120 hrs). The fairly swift hydrograph response is accentuated by a number of factors: (i) storm water reaches the stream via surface runoff within minutes as most of the catchment landscape is steep with limited depression storage; (ii) the soils are generally shallow with low infiltration capacity; and (iii) the storm water holding potential of the forest cover is probably low considering the alterations for agriculture and settlement. In totality, these factors have major implications on hydrological processes. Typically they result in the generation of elevated quick flow, with both high magnitudes and early peaks in the stream hydrograph following rainstorm events.

Storm-induced transients

Besides the dramatic effect on the stream hydrograph, storm-induced runoff in pastoral catchments could transport large amounts of sediments and other contaminants. This may include nutrients, organic matter and pathogens from farmland and settled areas. Table 3 shows the magnitude of pollution loads passing through Turkana Flats during transient events in comparison to levels observed at base flow. Transient loads of pollutants were several orders of magnitude higher during storm-induced events. In particular, the estimated load of suspended solids was striking; 778,000 kg day^{-1} during transients compared to 150 kg day^{-1} at base flow. The former corresponds to 0.06 tonnes ha^{-1} day^{-1}, when expressed over the contribution area (12000 ha). Most of the material is probably generated by runoff from outside the stream channel. But sloughing of the stream banks, as well as within-channel degradation of the streambed and resuspension are important. The estimated sediment load during rainfall events from different land use types in the NRC is generally high. Raude *et al.* (2007) recorded 0.04, 0.35 and 1.45 tonnes ha^{-1} day^{-1} of sediment load from forest cover, grazing and farmland, respectively, with field rainfall simulations. This is higher compared to within-stream estimates of the present study or those made by Otieno *et al.* (2006), who reported an average load of 0.02 tonnes ha^{-1} day^{-1} at the middle reaches in the vicinity of farmlands and settlements. The differences might have emanated from the different methods employed and possibly the changes in land use cover over since. In any case, eroded sediments are transported quickly with increase in rainfall intensity and deposited downstream as the runoff velocity weakens. This kind of soil erosion is a major cause of land and water degradation in tropical regions (Owino *et al.* 2006). Apart from impoverishing soil

Table 2 | Hydrological characteristics of transient flow events in 2006 and details of the inciting storms

Date when storm occurred	Type of storm	Duration of storm	Rainfall at Egerton (St. No. 09035092)	Response time to reach peak flow	Peak flow achieved	Duration of the descending limb
June 26, 2006	Rainstorm	3 hrs	40 mm day^{-1}	$<\frac{1}{2}$ hr	3.2 m^3 sec^{-1}	$<$48 hrs
August 6, 2006	Rainstorm	1 hr	21 mm day^{-1}	$<\frac{1}{4}$ hr	1.5 m^3 sec^{-1}	$<$10 hrs
August 27, 2006	Hailstorm	4 hrs	25 mm day^{-1}	$>$1 hr	3.9 m^3 sec^{-1}	$>$72 hrs
November 23, 2006	Rainstorm	6 hrs	68 mm day^{-1}	$>$2 hrs	6.2 m^3 sec^{-1}	$>$120 hrs
December 26, 2006	Rainstorm	4 hrs	25 mm day^{-1}	$>$1 hr	1.8 m^3 sec^{-1}	$<$72 hrs

Table 3 | Mean ($n = 4$) loads of pollutants at Turkana Flats in transient and base flow conditions

Response factor	Flow ($m^3\,day^{-1}$)	BOD_5 ($kg\,day^{-1}$)	TSS ($kg\,day^{-1}$)	TP ($kg\,day^{-1}$)	TN ($kg\,day^{-1}$)
Transients (rainstorms)	247,000	8,400	778,000	550	100
Wet weather flow	2,800	30	150	0.8	1.4
Transients (In-stream activities)	890	20	50	0.3	0.6
Dry weather flow	890	10	10	0.2	0.5

and lowering agricultural productivity, the erosion and eventual deposition of large amount of sediments affects receiving water bodies (Yang *et al.* 2009). For instance, deposition of fine sediments at impacted sites along Njoro River is known to reduce invertebrate densities, especially the seemingly sensitive taxa (Kibichii *et al.* 2007). Such sites are less attractive for colonization by invertebrates given that the substrate can be easily mobilized downstream (Bretschko 1995). Besides, cobbles covered by silt are less likely to be colonized by periphyton, a major food source for several scrapping macro-invertebrates communities in gravel-bedded streams (Kibichii *et al.* 2007).

Further downstream in receiving lake environments, primary productivity could be distorted as the phytoplankton layer becomes light limited with the suspension of fine sediments (Schreiber *et al.* 1996). In the absence of fine sediments in suspension, nutrients transported by event pulses during rainstorms could enrich plankton growth. Storm-generated runoff in agricultural catchments is rich in agrichemicals, including nutrients such as P and N (Owino *et al.* 2006; Yang *et al.* 2009). In the NRC, farming activities entail widespread use of both organic manure and inorganic fertilizers such as diammonium phosphate (Mokaya *et al.* 2004). On average, 57 kg ha^{-1} of diammonium phosphate and 2,710 kg ha^{-1} of manure is used during the main growing season (April–October) (Eric Bett, personal communication). Organic manure may include livestock and plant biomass combined and this is often used to supplement fertilizer input mostly on small-holder farms. As farming is largely rain-fed, the application of both organic and inorganic fertilizers coincides with wet weather. Given the very steep terrain and the easily erodible nature of the soils, the likelihood for entrainment of dissolved and/or sediment adsorbed fractions is high during storm-induced events. Actually, both P and N loads increased significantly ($p < 0.05$) at the peak of the rising limb of the stream hydrograph (Table 3). It is believed that most of the P loading was sediment-associated given the significant and strong positive correlation between the two ($R^2 = 0.78$; $p < 0.05$). Sediment runoff could also play an important role in the transport of easily degradable organic matter and faecal matter in pastoral catchments. Because both contaminants are associated with sediments, BOD_5 levels and FIB densities increased concurrently with the supply of suspended solids at the peak of rising limb of the stream hydrograph (Table 4 and Figure 3). The introduction of easily degradable organic matter in aquatic environments increases the *in-situ* oxygen demand, with the likelihood of oxygen depletion within a couple of days. This may, in turn, affect the available oxygen needed by organisms, especially, those which cannot survive in oxygen-stress environments. Dissolved oxygen levels tended to rise ($>9\,mg\,l^{-1}$ in two instances) following rainstorm events, probably from flushing of oxygen-deficient anaerobic pockets within the stream channel and/or due to aeration from turbulent mixing as stream flow increased. However, oxygen levels in the stream decreased in some instances to $<3\,mg\,l^{-1}$ as the stream returned to base flow conditions few days later. This indicates that the impact of bacteria degradation on the *in-situ* oxygen demand, most likely, took place few days after degradable organic matter was introduced into the stream. On the other hand, the apprehension over the introduction of faecal matter in water bodies is largely to do with the ramifications for human health, especially when such water bodies are used for recreation or as water sources for domestic use. Faecal matter, especially, from people and livestock may harbour several pathogenic microbes, which are transmitted during exposure to contaminated water. A recent health risk survey on the Njoro River revealed that the potential risk of gastrointestinal illnesses among exposed populations at several water abstraction points along the stream critically exceeded

Table 4 | Pre- and post-storm ambient levels of water quality variables at Turkana Flats

Dates	Flow × 10^{-3} ($m^3\,sec^{-1}$)	TSS ($mg\,l^{-1}$)	Turbidity ($UV_{347}\,m^{-1}$)	Temp. (°C)	Cond. ($\mu S\,cm^{-1}$)	DO ($mg\,l^{-1}$)	BOD_5 ($mg\,l^{-1}$)	TP ($m\,l^{-1}$)	TN ($mg\,l^{-1}$)
June 13	8	21	21	14.9	259	3.9	16.1	0.26	0.33
June 20	5	75	41	18.8	266	2.8	19.0	0.27	0.54
June 26 *	3,167	3,600	1,082	17.2	194	6.2	26.9	2.31	0.43
June 27	238	356	221	18.4	193	6.4	15.8	1.37	0.30
June 28	40	40	37	17.2	191	6.6	9.4	0.21	0.26
June 29	27	36	33	17.2	191	6.6	7.4	0.20	0.26
July 25	40	64	22	16.7	196	5.6	10.0	0.24	0.48
Aug. 5	43	64	37	16.7	196	5.6	10.0	0.25	0.46
Aug. 6*	1,518	1,517	898	16.3	191	6.1	25.4	2.19	0.42
Aug. 7	277	410	239	17.4	157	6.1	14.4	1.03	0.39
Aug. 8	100	87	43	14.6	121	6.2	7.5	0.13	0.39
Aug. 9	55	48	39	15.1	121	6.2	6.5	0.15	0.37
Aug. 15	30	48	39	16.5	159	5.8	9.4	0.27	0.51
Aug. 22	49	40	38	16.3	159	5.8	9.4	0.33	0.52
Aug. 27*	3,881	3,433	1,399	10.1	138	9.2	43.4	2.19	0.37
Aug. 28	416	443	233	16.2	137	6.8	17.3	1.14	0.33
Aug. 29	79	80	40	15.4	140	6.7	7.2	0.19	0.31
Aug. 30	68	57	30	15.4	158	6.6	7.1	0.16	0.24
Nov. 22	267	40	37	17.9	114	6.4	10.4	0.11	0.15
Nov. 23*	6,237	312	149	13.8	82	9.1	16.8	1.72	0.12
Nov. 24	1,940	128	63	15.8	83	8.1	8.1	0.76	0.11
Nov. 25	1,221	44	36	15.4	82	7.9	2.2	0.10	0.10
Nov. 26	455	38	26	15.4	84	7.3	2.3	0.10	0.09

Note: In particular, the sharp increase in stream flow, suspended solids (TSS), turbidity, BOD_5 and total phosphorus (TP), and the corresponding decrease in conductivity (Cond.) and total nitrogen (TN) levels on the dates when storm occurred (shown with asterisk).

acceptable threshold levels for bathing and drinking (Yillia *et al.* 2009). This means that the stream is unsuitable for bathing or drinking without treatment but many people (over 70,000 riparian inhabitants) depend entirely on the stream for their daily water needs since it is the only main source of water in the area (Yillia *et al.* 2008*a*).

Two major forms of concentration-discharge relationships were observed during storm-induced transients. A dramatic rise in the concentration of suspended solids, BOD_5 and total P as the stream attained peak flow and a corresponding decrease for conductivity and total N (Table 4). The former response was also observed for the FIB, which were generally 2–3 orders of magnitude higher than pre-storm base flow levels (Figure 3). The increase in pollution levels in this manner during transient storm events is typical for streams draining pastoral catchments.

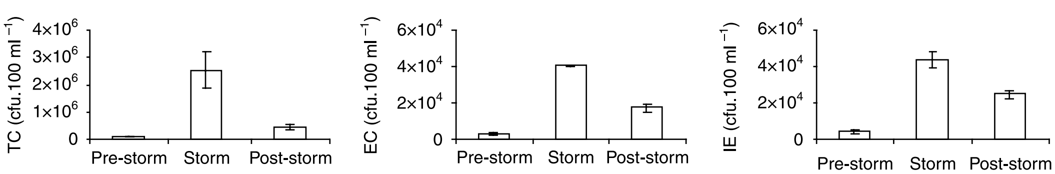

Figure 3 | Mean levels ($n = 4$) of Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) at Turkana Flats during storm induced transients (storm), <7 days before (pre-storm) and 1 day after (post-storm). Vertical bars indicate the standard deviation.

The increase emanates from the rapid delivery of pollutants via runoff as the sources of mobilized pollutants are usually within reach of the stream for them to be transported quickly (Iqbal 2002; Bowes *et al.* 2005). In the NRC, the most likely sources are farmlands and residential plots where loose soil and debris accumulate during dry weather antecedent conditions (Yillia & Kreuzinger 2009). Antecedent conditions could last for four to five months in the dry season before the onset of rains. But even in wet season, dry spells can occur erratically, during which loose materials accumulate before the next rainfall event. Such dry spells are usually short-lived compared to the dry season antecedent weather. Invariably, the magnitude of materials transported via surface runoff depends on the duration of these antecedent conditions, as well as the intensity and duration of the runoff-generating storm. The concentration decrease for conductivity and total N at peak flow suggested dilution by rainwater of: (i) runoff-derived soluble components; and (ii) within-stream channel soluble constituents as stream flow increased. It is known that the rainwater has a lower conductivity compared to the runoff it generates. Therefore, it acted as dilution water for the soluble constituents. 80–95% of total N in the stream occurs in the soluble state, mainly, in the form of NO_3-N and NH_4-N (Yillia & Kreuzinger 2009). In contrast, total P is largely ($>$ 80%) in the particulate/adsorbed form. There was a slight decline in the concentration of pollutants at the base of the descending limb of the stream hydrograph following each storm event (Table 5). This phenomenon occurred before the next base flow was established and the return of regular pollution levels. It was distinctive around 48–72 hrs of runoff recession during which ambient pollution levels were significantly ($p < 0.05$) lower than pre-storm base flow levels. This period may be considered as a short-lived post-disturbance recovery phase of improved water quality before the next base flow was realized. Probably, it was an offshoot of delayed intrusion of sub-surface flow from the predominantly forested upper catchment, which brought moderately contaminated flow to the middle reaches after precipitation and surface runoff had subsided. Also it appears there was a finite supply of contaminants which seemed to deplete at the receding limb of the stream hydrograph. It is thought that this supply regenerates between transient storm events during antecedent conditions. The rebound of pollution levels pending the realization of post-storm base flow conditions and/or the interruption by a subsequent transient storm event could naturally emanate from within-stream processes. This can occur as pollutants became more concentrated with the decrease in stream flow. Another reason is the possible introduction of fresh contaminants through direct input from the chain of in-stream activities of people and livestock along the stream (Yillia *et al.* 2008*a*,*b*).

Transient episodes provoked by in-stream activities

In-stream activities are described as the actions of people and livestock that take place repeatedly within or besides stream channels (Mathooko 2001; Yillia *et al.* 2008*a*). Compared to storm-induced transient events, the pollution loads generated by the episodes provoked by in-stream activities of people and livestock were within 3–4 orders of magnitude lower. However, in-stream activities are widespread along the stream and they occur daily. The main activities include abstraction of water for domestic use, washing of clothes, swimming and bathing, as well as waste disposal and watering of livestock (Yillia *et al.* 2007*a*). Therefore the cumulative effect of these activities on stream flow and water quality is substantial, especially, in dry weather when they are more frequent (Yillia *et al.* 2008*a*).

Table 5 | Mean ($n = 4$) levels of pollutants illustrating post-storm improvement in water quality 3 days after storm-induced transient events

Period	Flow × 10^{-3} (m^3 sec^{-1})	BOD_5 (mg l^{-1})	TSS (mg l^{-1})	PO_4-P (mg l^{-1})	TP (mg l^{-1})	NH_4-N (mg l^{-1})	NO_3-N (mg l^{-1})	TN (mg l^{-1})
Pre-storm (<7 days before)	30	12.8	60	0.06	0.28	0.13	0.31	0.51
Transient (storm-induced)	2,900	31.9	2,850	–	2.32	–	–	0.41
Post-storm (3 days after)	50	7.0	47	0.04	0.17	0.08	0.22	0.29
Post-storm (>7 days after)	35	9.1	50	0.05	0.23	0.09	0.27	0.42

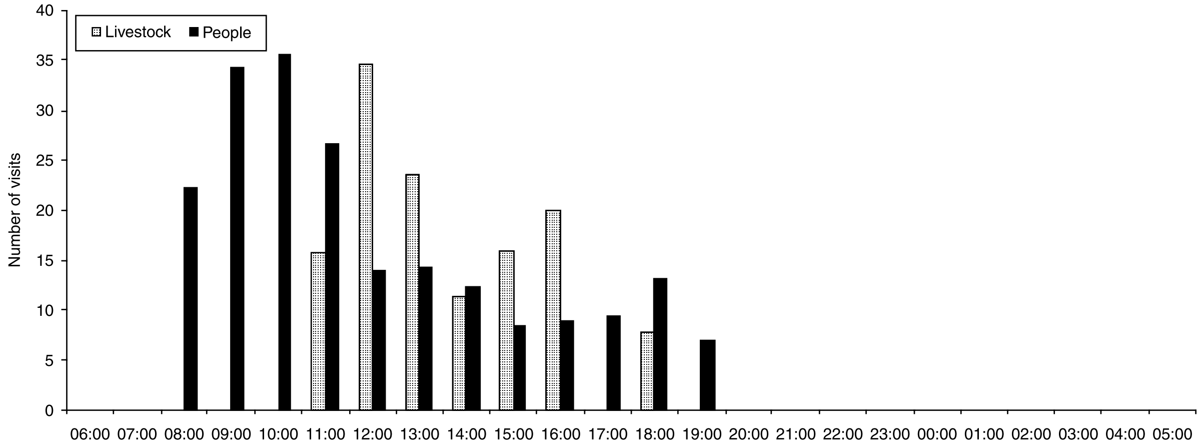

Figure 4 | Hourly tally of people and livestock showing diurnal variability of visits at Turkana Flats during dry weather (January–April) in 2006.

In reality, in-stream activities yielded significantly ($p < 0.05$) more loads of pollutants compared to dry weather base flow levels (Table 3). Typically, they start after daybreak with human visits (7 a.m. to 8 a.m.), followed afterwards by livestock to water at about 10 a.m. (Figure 4). There are usually two peaks in activities: a pronounced peak between 9 a.m. and 12 noon, and a smaller and less distinct peak in the evening at about 6 p.m. Consequently, the transient pollution episodes they generate are linked to this diurnal pattern of visits, as well as the duration and intensity of the type of activity that is undertaken (compare Figures 4–6). Usually, most activities last for a short duration, sometimes a couple of minutes only. For instance, water abstraction with small containers from the stream bank may last less than 5 minutes whereas washing of clothes usually takes longer (2–3 hours). Watering of livestock could last 10–15 minutes. The concomitant increase in pollution levels downstream of activities was more dramatic with turbidity, suspended solids and the FIB (Figures 5 and 6). This is largely because during activities, people and animals wade through the stream. In so doing, they disturb settled matter, especially fine sediments including attached bacteria and other contaminants that were introduced previously (Yillia et al. 2008a,b). It is known that the pattern of bacteria resuspension in alluvia streams is very much related to the transport characteristics of the sediments to which they are attached (Jamison et al. 2005). Sediments provide favorable environment, which improves the survival and possible growth of bacteria (Burton et al. 1987; Sherer et al. 1992). This might explain the diurnal pulse in FIB levels in

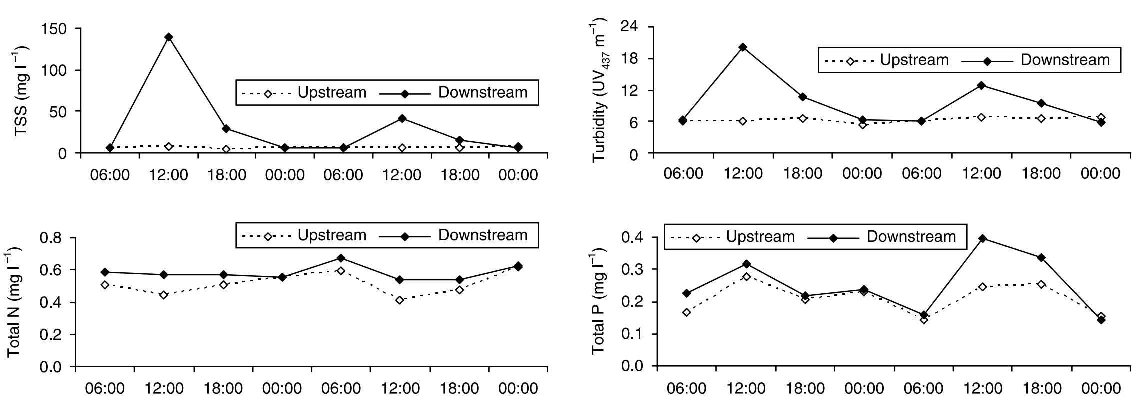

Figure 5 | Mean levels ($n = 4$) of TSS, Turbidity, total N and total P illustrating the effect of diurnal transients provoked by in-stream activities on two consecutive days for at Turkana Flats in dry weather (January–April).

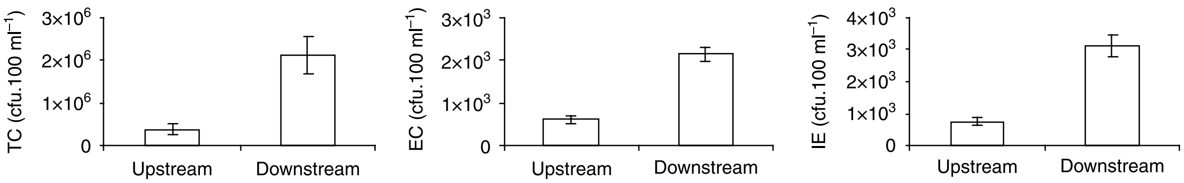

Figure 6 | Mean levels ($n = 4$) of Total Coliforms (TC), *Escherichia coli* (EC) and intestinal enterococci (IE) upstream and downstream of in-stream activities (11 a.m.–12 midday) at Turkana Flats in dry weather. Vertical bars indicate the standard deviation.

concomitance with turbidity and suspended solids. As the transient pollution loads generated are usually short-lived, it is believed that much of the water quality problems caused by in-stream activities usually flow downstream without much notice (Yillia *et al.* 2008*a*). But whether such water quality fluctuations are strictly transient is ambivalent because transients are sometimes understood as isolated and aperiodic events that occur in addition to the seasonal and diurnal variations observed in streams (Whitefield & Wade 1996). It is evident from the above description that in-stream activities are not remote events neither are they irregular. In reality, they are habitual and are quite predictable (Mathooko 2001; Yillia *et al.* 2008*a*,*b*). This also true for the water quality problems associated with them (Yillia *et al.* 2008*a*,*b*). However, pollution levels during in-stream activities generally exceed the diurnal variations usually observed in the absence of these activities (Yillia *et al.* 2008*a*,*b*). It is well known that all systems are subject to a wide spectrum of dynamic perturbations, with low frequency fluctuations over decades and years usually viewed as either long-term or quasi-equilibrium conditions (Beck 1996*a*). Therefore, any short-term perturbations, which force the equilibrium state above that low frequency oscillation, could be viewed as transient even if they are regular and predictable. This is important when scientific or legal evidence is required to justify management actions needed to address specific pollution problems. Because of their predictability, in-stream activities in the NRC have been monitored with some reasonable degree of certainty without online equipments (Mathoko 2001; M'Erimba *et al.* 2006; Yillia *et al.* 2008*a*,*b*). However, careful preparation is necessary to incorporate issues, such as, the time of sampling, the choice of monitoring points at a disturbed stream site or the number of representative samples that may be required to optimize results (Yillia *et al.* 2008*a*).

CONCLUSION

The study showed the importance of two transient pollution events that aid the transfer of pollutants in a pastoral catchment in southwestern Kenya. Storm-induced transients lasted longer and produced substantial loads of pollutants compared to the diurnal transient episodes provoked by in-stream activities of people and livestock. However, in-stream activities are widespread, they occurred daily, and they have considerable effect on dry weather base flow. Both events affect within-stream channel processes, including water quality, with possible attendant effects on the receiving lake and the health of riparian inhabitants. Therefore, measures are required to regulate in-stream activities and reduce the mobilization of pollutants through surface runoff. This may include protection of headwater areas and the riparian zone by preserving forest and grass cover to reduce rapid runoff and soil erosion. Further studies could focus on: (i) sediment characteristics and transport dynamics; (ii) bacteria survival and nutrient sorption to sediments; and (iii) hydraulic conditions for the entrainment of sediment associated contaminants in runoff.

ACKNOWLEDGEMENTS

The study was financed by the Austrian Government through the Academic Co-operation & Mobility Unit (ACM) of the Austrian Exchange Service (ÖAD). Dr Adiel Magana, Dr Nzula Kitaka and Prof Jude M. Mathooko are differentially acknowledged for additional logistic support. Special thanks to Kenneth Kisombei and Geoffrey Ongondo for technical assistance during the study.

REFERENCES

APHA 1995 *Standard Methods for the Examination of Water and Wastewater*, 19th edition. American Public Health Association, Washington, DC.

Beck, M. B. 1996*a* Transient pollution events: acute risk to the aquatic environment. *Water Sci. Technol.* **33**(2), 1–15.

Beck, M. B. 1996*b* Uncertainty, risk, and transient pollution events: a survey. *Water Sci. Technol.* **33**(2), 34–41.

Beck, M. B., Adeloye, A. J., Finney, B. A. & Lessard, P. 1991 Operational water quality management: transient events and seasonal variability. *Water Sci. Technol.* **24**, 257–265.

Bowes, M. J., Housea, W. A., Hodgkinsonb, R. A. & Leach, D. V. 2005 Phosphorus-discharge hysteresis during storm events along a river catchment: the River Swale, UK. *Water Res.* **39**(5), 751–762.

Bretschko, G. 1995 Tropical River Ecology Initiative. *Proceedings of the First workshop on the Limnology of Njoro River* (31st January–18th February, 1994) Egerton University, Njoro, Kenya.

Burton, G., Gunnison, D. & Lanza, G. 1987 Survival of pathogenic bacteria in various freshwater sediments. *Appl. Environ. Microbiol.* **53**, 633–638.

Iqbal, M. Z. 2002 Nitrate flux from aquifer storage in excess of baseflow contribution during a rain event. *Water Res.* **36**, 778–792.

Jacobsen, J. L., Madsen, H. & Harremoës, P. 1996 Modelling the transient impact of rain events on the oxygen content of a small creek. *Water Sci. Technol.* **33**(2), 177–185.

Jamison, R. C., Joy, D. M., Lee, H., Kostaschuk, R. & Gordon, R. J. 2005 Resuspension of sediment-associated *Escherichia coli* in a natural stream. *J. Environ. Qual.* **34**, 581–589.

Kibichii, S., Shivoga, W. A., Muchiri, M. & Miller, S. N. 2007 Macroinvertebrate assemblages along a land-use gradient in the upper River Njoro watershed of Lake Nakuru drainage basin, Kenya. *Lakes Reserv. Res. Manage.* **12**, 107–117.

Mathooko, J. M. 2001 Disturbance of a Kenyan Rift Valley Rift Valley stream by the daily activities of local people and their livestock. *Hydrobiologia* **458**, 131–139.

Mathooko, J. M. & Kariuki, S. T. 2000 Disturbances and species distribution of the riparian vegetation of a Rift Valley stream. East African Wildlife Society. *Afr. J. Ecol.* **38**(2), 123–129.

M'Erimba, C. M., Mathooko, J. M. & Leichtfried, M. 2006 Variations in coarse particulate organic matter in relation to anthropogenic trampling on the banks of the Njoro River, Kenya. *Afr. J. Ecol.* **44**(2), 282–285.

Mokaya, S. K., Mathooko, J. M. & Leichtfried, M. 2004 Influence of anthropogenic activities on water quality of a tropical stream ecosystem. *Afr. J. Ecol.* **42**(4), 281–288.

Otieno, H., Onyando, J. O. & Saenyi, W. W. 2006 Estimation of peak direct runoff and sediment yield from Upper River Njoro Catchment using AgNPS model. *Proceedings of International Symposium on Soil Physics and Rural Water Management* (SOPHYWA), September 28–29, 2006, Vienna, Austria, 147–150.

Owino, J. O., Owido, S. F. O. & Chemelil, M. C. 2006 Nutrient in runoff from a clay loam soil protected by narrow grass strips. *Soil Tillage Res.* **88**, 116–122.

Raude, J. M., Onyando, J. O. & Owino, J. O. 2007 Estimation of soil loss from selected land use practices under varying rainfall intensity in River Njoro catchment in Kenya. Book of Abstracts, 5th International Congress of the European Society for Soil Conservation, June, 25–30, 2007, Palermo, Spain, p. 164.

Schreiber, J. D., Smith, S., Jr & Cooper, C. M. 1996 The occurrence, distribution, and remediation of transient pollution events in agricultural and silvicultural environments. *Water Sci. Technol.* **33**(2), 17–26.

Schreiber, J. D., Rebich, R. A. & Cooper, C. M. 2001 Dynamics of diffused pollution from US southern watersheds. *Water Res.* **35**(10), 2534–2542.

Sherer, B., Miner, R., Moore, J. & Buckhouse, J. 1992 Indicator bacteria survival in stream sediments. *J. Environ. Qual.* **21**, 591–595.

UNEP/WHO 1996 Water Quality Monitoring–a practical guide to the design and implementation of freshwater quality studies and monitoring programmes. ISBN 0-419-22320-7 (Hbk), 0-419-21730-4 (Pbk).

Whitfield, P. H. & Wade, N. L. 1992 Monitoring transient water quality events electronically. *Water Res. Bull.* **29**, 703–711.

Whitfield, P. H. & Wade, N. L. 1996 Transient water quality events in British Columbia coastal stream. *Water Sci. Technol.* **33**(2), 151–161.

Yang, J. L., Zhang, G. L., Shi, X. Z., Wang, H. J. & Cao, Z. H. 2009 Dynamic changes of nitrogen and phosphorus losses in ephemeral runoff processes by typical storm events in Sichuan basin, Southwest China. *Soil Tillage Res.* **105**, 292–299.

Yillia, P. T. & Kreuzinger, N. 2009 Net flux of pollutants at a reduced spatial scale–an index of catchment vulnerability. *Water Sci. Technol.* **59**(1), 109–116.

Yillia, P. T., Kreuzinger, N. & Mathooko, J. M. 2008*a* The effect of in-stream activities on the Njoro River, Kenya. Part I: stream flow and chemical water quality. *Phys. Chem. Earth* **33**(8), 722–728.

Yillia, P. T., Kreuzinger, N. & Mathooko, J. M. 2008*b* The effect of in-stream activities on the Njoro River, Kenya. Part II: microbial water quality. *Phys. Chem. Earth* **33**(8), 729–737.

Yillia, P. T., Kreuzinger, N., Mathooko, J. M. & Ndomahina, E. T. 2009 Microbial risk assessment with the OAEL approach at water abstraction points in rural Kenya. *Phys. Chem. Earth* **34**(13–16), 790–798.