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Variation in material transport and water chemistry along a large ephemeral river in the Namib Desert

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SUMMARY

1. The chemical characteristics of floodwaters in ephemeral rivers are little known, particularly with regard to their organic loads. These rivers typically exhibit a pronounced downstream hydrological decay but few studies have documented its effect on chemical characteristics and material transport. To develop a better understanding of the dynamics of floods and associated material transport in large ephemeral rivers, floods of the ephemeral Kuiseb River in south-western Africa were tracked and repeatedly sampled at multiple points along the river's lower 220 km.
2. We quantified the composition and transport of solute and sediment loads in relation to longitudinal hydrological patterns associated with downstream hydrological decay. Source and sink areas for transported materials were identified, and the composition and transport dynamics of the organic matter load were compared to those described from more mesic systems.
3. Concentrations of sediments and solutes transported by floods in the Kuiseb River tended to increase downstream in association with pronounced hydrological decay. The contribution of particulate organic matter to total organic load is among the highest recorded, despite our observation of unusually high levels of dissolved organic matter. Hydrological decay resulted in deposition of all transported material within the lower Kuiseb River, with no discharge of water or materials to the Atlantic Ocean.
4. Our results suggest that longitudinal variation in surface flow and associated patterns of material transport renders the lower Kuiseb River a sink for materials transported from upstream. The downstream transport and deposition of large amounts of labile organic matter provides an important carbon supplement to heterotrophic communities within the river's lower reaches.

Keywords: material transport, water chemistry, ephemeral river

Introduction

Unlike most perennial systems, ephemeral rivers exhibit a pronounced downstream hydrological decay, attributable to transmission losses associated with infiltration and evaporation (Graf, 1988). Downstream attenuation in both peak discharge and total flow volume are perhaps the best known characteristics of ephemeral rivers and have been documented for systems of varying sizes (Leopold & Miller, 1956; Picard & High, 1973; Sharma *et al.*, 1984a; Schick, 1988; Walters, 1989; Jacobson *et al.*, 1995). Associated with this attenuation is a downstream decrease in stream power and a corresponding increase in alluviation (Bull, 1979). The resulting alluvial deposits are perhaps the most extensively studied aspect of ephemeral systems (Picard & High, 1973; Baker, Kochel & Patton, 1988; Graf, 1988; Warner, 1988).

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While the episodic floods that form these alluvial deposits have long fascinated the desert traveller (Van Dyke, 1901), reports of their chemical composition and transport dynamics are scarce. Fisher & Minckley (1978) were the first to document temporal variation in the chemical characteristics of a 'flash flood', sampling floodwaters in Sycamore Creek, an intermittent stream in the Sonoran Desert. The high levels of dissolved and particulate material revealed the importance of such floods, despite their brief duration, to the mass transport of materials from dryland catchments to downstream systems.

Sharma *et al.* (1984a,b) provided details on the spatial variation in transmission losses, water chemistry, and patterns of sediment transport during a flood in the ephemeral Luni River in arid northwestern India. This study was the first to examine changes in chemical characteristics as a desert flood travelled downstream, in this case over a distance of several hundred kilometres. The concentrations of sediment and selected ions increased as peak discharge and total flow volume decreased. In both studies, however, chemical analyses were restricted to inorganic constituents. With the exception of Fisher & Minckley's (1978) report that 11% of the total suspended sediments was organic matter, no information was provided on the organic loads transported by these floods.

While recent studies have more closely examined organic matter dynamics in intermittent Sycamore Creek (Fisher & Grimm, 1985; Jones, Fisher & Grimm, 1996; Jones *et al.*, 1997), patterns in ephemeral systems remain unknown. Further study is warranted because the hydrological decay exhibited by ephemeral systems is likely to result in patterns of material transport and deposition that diverge from those of their more mesic counterparts. In addition, ephemeral rivers occur throughout the arid and semiarid regions that cover roughly a third of the world's surface (Thornes, 1977), making them one of the most common, yet least known, types of fluvial ecosystems.

To assess the influence of hydrological decay on the spatial patterns of water chemistry and material transport, we sampled floods travelling down the ephemeral Kuiseb River in western Namibia from 1993 to 1995. In particular, we quantified the composition and transport of the organic load in relation to longitudinal hydrological patterns associated with downstream hydrological decay. Source and sink areas for transported materials were identified, and the composition and transport dynamics of the organic matter load were compared to those described from more mesic systems.

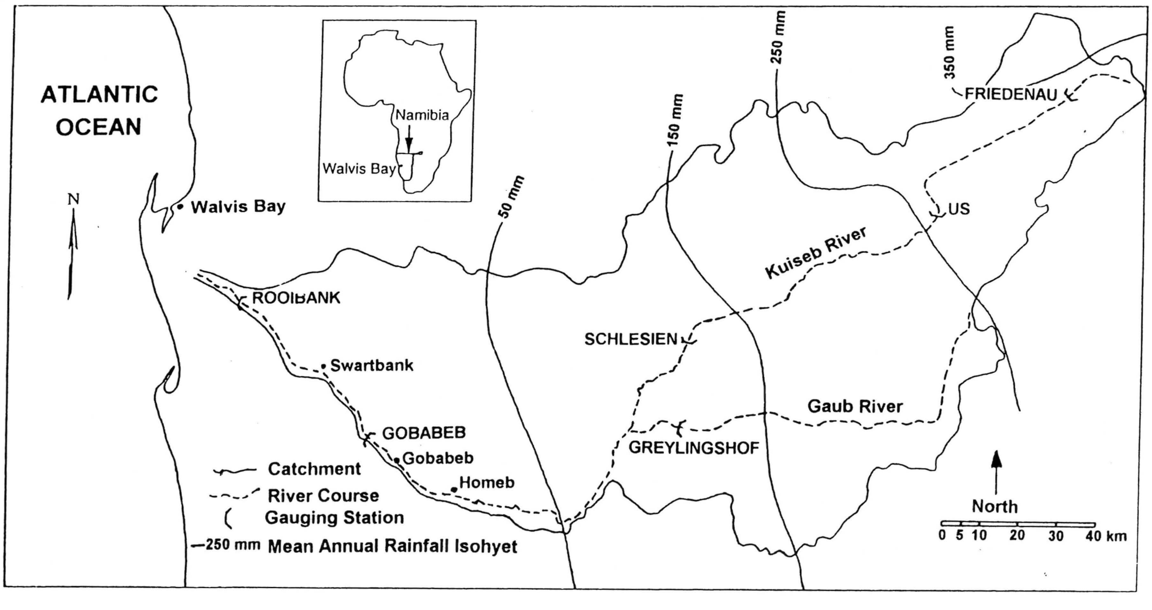

Fig. 1 Gauging stations, key geographic features, and mean annual rainfall isohyets within the Kuiseb River catchment in western Namibia.

Methods

Study area

The Kuiseb River drains a catchment of ≈ 14 700 km^2 in west-central Namibia, flowing for 560 km from its headwaters to the Atlantic Ocean. The driest country in southern Africa, Namibia is named for the coastal Namib Desert, running the length of the country and extending inland ≈ 150 km to the base of the Great Western Escarpment. Associated with the desert is a strong east–west climatic gradient. Mean annual rainfall exceeds 350 mm in the headwaters, at an elevation of about 2 000 m on the inland plateau. Moving westward, mean annual rainfall drops to about 100 mm at the eastern edge of the Namib Desert at the escarpment's base, then to near zero at the coast (Namibian Weather Bureau). Evaporation is high throughout the catchment, exceeding rainfall by 7–200 times (Lancaster, Lancaster & Seely, 1984). As a result, surface flow occurs in direct response to strong convective storms, primarily during the summer months, and rapidly ends after the cessation of localised rains.

From the headwaters westward the river has eroded a shallow, sinuous valley into schists and quartzites, the source of much of the sandy bedload transported within the lower river (Ward, 1987). West of the escarpment separating the inland plateau from the coastal plains, the river has incised a deep canyon (> 200 m) in similar rocks. The river is highly confined within this canyon, often flowing over bedrock with no alluviation due to the comparatively steep gradient (0.003–0.004 m m^{-1}) and narrow channel. This canyon broadens some 65 km from the coast, whereafter the river occupies a broad, shallow valley which finally becomes indistinct within 20 km of the coast. There, low crescentic dunes cross the river, producing several poorly defined channels that terminate near Walvis Bay. Gradients below the canyon average 0.001–0.002 m m^{-1}, increasing to more than 0.004 m m^{-1} within 60 km of the coast, resulting in a slightly convex longitudinal profile in the lower river. When in flood, the river's lower reaches transport a sandy bedload and a suspension load high in silts. The sandy channel sediments within the lower 150 km are largely devoid of cobble or bedrock, excluding occasional bedrock dikes that cross the channel and form local knick points in the longitudinal profile (Ward, 1987). Depth to groundwater averages from 5 to 15 m in the lower reaches of the river.

Table 1 Catchment area, elevation, channel gradient, mean annual runoff (MAR), and mean annual peak discharge (MAPD) for hydrological gauging stations within the lower Kuiseb River

Station	Catchment (km^2)	Elevation (m)	Gradient (mm^{-1})	MAR (m^3)	MAPD (m^3 s^{-1})
Schlesien	6 520	760	0.0040	6.59×10^6	71.9
Greylingshof	2 490	720	0.0055	2.77×10^6	68.0
Confluence	≈ 9 500	620	0.0035	9.51×10^6	–
Gobabeb	11 700	360	0.0030	4.65×10^6	31.9
Rooibank	14 700	120	0.0039	0.64×10^6	7.4

Runoff and discharge values are based on the annual flow series from 1979 to 1993. Confluence MAR was calculated from the annual sums of Schlesien and Greylingshof; MAPD was not estimated.

The lower Kuiseb River has comparatively lush riparian forest, offset by the adjacent sand and rock desert (Theron *et al.*, 1980; Seely & Griffin, 1986). *Faidherbia albida* is the dominant woody species, contributing organic matter to the channel and floodplain in the form of wood and leaves, as well as dry fruits (seed pods) dropped prior to summer rains (Seely *et al.*, 1979/80–1980/81). The tree occurs only sporadically within the escarpment and canyon reaches but extensively on downstream alluvial deposits associated with the broader channel and floodplain (Theron *et al.*, 1980).

Discharge

Surface flow in the Kuiseb River is routinely monitored by the Namibian Department of Water Affairs (DWA) via a series of automatic gauging stations along the river's mainstem and tributaries. Distinct longitudinal trends are evident among the hydrological records from these stations, particularly among the mainstem stations (Jacobson, 1997). Mean annual runoff (MAR) and mean annual peak discharge (MAPD) exhibit a strong decay from the base of the escarpment westwards to the coast (Table 1).

Records from two gauges were used to monitor flow out of the upper catchment where most floods originate: one on the mainstem of the Kuiseb River (Schlesien), ≈ 172 km above the Gobabeb gauge, and another on the Gaub River (Greylingshof), the

Kuiseb's main tributary, ≈ 20 km upstream of the Gaub–Kuiseb confluence and about 147 km above the Gobabeb gauge. Flow within the study reach was measured at the Gobabeb gauge and at Rooibank, 57 km downstream. These stations, equipped with automatic chart recorders, provided a record of the flood hydrograph from which the peak discharge (m^3 s^{-1}) and total flow volume (m^3) for each flood were calculated.

The DWA provided access to hydrographic records and previously established rating curves, which were used to calculate discharge. Total flow volumes were estimated by integrating discharge over the course of the hydrograph, using the trapezoidal rule for unequally spaced x-values (Sigma Plot, Jandel Corporation). Gauge floats frequently jammed during recession flows due to the high particulate loads carried by floods. Recession curves were then estimated, based on floods of similar magnitudes previously recorded at the individual stations. Gauges occasionally malfunctioned completely, preventing any approximation of flood volume.

Floodwater analysis

Water samples were collected in acid-washed, 500-mL polyethylene bottles. Whenever possible samples were collected mid-channel, although this was not possible during high-magnitude discharges. When safety considerations precluded such sampling, samples were collected within 2 m of the bank. In all cases, the uncapped bottle was lowered into the flow to the channel bottom or to a maximum depth of about 0.5 m and retracted at an even rate to approximate a depth-integrated sample. Samples were taken from bores (leading edges), at peak discharge, and during recession flows. One flood was intercepted and tracked downstream following its exit from the escarpment, providing an opportunity to examine the longitudinal variation in water chemistry and organic matter transport.

Water samples were stored unpreserved at 4 °C and filtered on return to the laboratory. Samples were prefiltered through a 1-mm sieve and filtered through preweighed Whatman GF/F glass fibre filters. Total suspended solids (TSS) were determined gravimetrically after drying filters to a constant weight at 90 °C. Fine particulate organic matter (FPOM) was determined as loss on ignition (550 °C, 2 h) of filtered materials and expressed as ash-free dry mass. Dissolved organic matter (DOM) was measured by dichromate oxidation (Maciolek, 1962), using a 20-mL aliquot of filtrate evaporated to dryness at 90 °C. Conductivity and pH were determined with a YSI Model 33 S-C-T and a Fisher Model 640 meter, respectively. Sodium, potassium, calcium, and magnesium were measured using a Phillips PU 9200/9390 atomic absorption spectrophotometer. Alkalinity was determined titrimetrically, using sulphuric acid, sulphate turbidimetrically, with $BaCl_2$, and chloride titrimetrically, with $AgNO_3$.

The concentration of coarse particulate organic matter (CPOM) transported in the leading edge of a flood was measured by sampling the bore and the subsequent flow using a 9-L bucket with a 30-cm opening. After sampling, contents were poured through a 1-mm sieve and the contents dried and weighed. Following flood recession, lateral deposits of FPOM and CPOM were sampled from replicated ($n = 4$) 1-m^2 plots randomly selected from along the flood's lateral strand line. Samples were collected at three sites separated by 25–40 km to examine longitudinal changes in POM transport in association with the hydrological decay. One-way analysis of variance (ANOVA) was used to compare means among sites (Zar, 1984).

Material transport rates (kg s^{-1}) were calculated for organic matter and suspended solids as the product of discharge (m^3 s^{-1}) and concentration (kg m^{-3}). The total mass of material transported past sampling points during a flood was estimated by integrating the material transport rates over the course of the hydrograph, using the trapezoidal rule for unequally spaced x-values (Sigma Plot, Jandel Corporation). No attempt was made to express transport rates or total mass values in terms of export per unit area of drainage basin. The large size of the catchment combined with the low density of rainfall recording stations prevented an accurate estimation of the location and spatial extent of source areas for individual floods.

Results

Discharge

A total of 12 floods occurred during the study period, although discharge data are only available for the 1993 and 1994 floods. The duration of individual floods ranged from 1 to 8 days at Gobabeb, with a mean of 3 days (SD = 2). Floods were preceded by a bore ranging from less than 5 cm to about 50 cm in height. Bore height increased in response to increasing discharge and channel gradient and decreased with increasing channel width. Flood bores travelled at an average speed of 2.1 m s^{-1} (SD = 0.1, n = 4) above Gobabeb and decreased to 0.8 m s^{-1} (SD = 0.1, n = 3) downstream, from Swartbank to Rooibank. The interval between bore arrival and peak discharge was short, ranging from 3 to 15 min. Flood rise and recession were both rapid, reflecting the importance of Hortonian overland flow in generating streamflow in dryland environments (Reid & Frostick, 1989). Multiple peaks often occurred, reflecting the influence of tributary inflows and multiple storm events. The peak discharge recorded during the period was 322 m^3 s^{-1}, associated with a flood in the Gaub River, the Kuiseb's main tributary, in January 1993. The discharge of all recorded floods decayed to zero within 440–550 km downstream of the headwaters. The furthest reach of the floodwaters varied over a distance of only 40 km during the three years. The maximum occurred in 1993 when the floods reached 550 km downstream from the headwaters; the minimum of 510 km occurred in 1995.

In January 1994 a 2-day flood was intercepted as it flowed out of the escarpment. The hydrological decay recorded during this event was characteristic of that associated with all observed floods. The initial floodwave originated in the Gaub River catchment, and a peak of 159 m^3 s^{-1} was recorded at the Greylingshof gauge, with a total flow volume of about 2.75 Mm^3 (million cubic meters). A second floodwave originated within the Kuiseb catchment above the Schlesien gauge, but was not recorded due to an instrument failure. Our observations of the flood and subsequent channel surveys suggest that it peaked at about 20 m^3 s^{-1} at the Schlesien gauge, with an estimated flow volume of around 2 Mm^3. The combined flow volume estimated for the Kuiseb–Gaub confluence was thus ≈ 4.75 Mm^3. A total of 2.3 Mm^3 was measured at the Gobabeb gauge, 140 km below the confluence, representing a transmission loss of about 52%, or 0.37% km^{-1}.

Transmission losses increased significantly from the Gobabeb gauge down to Rooibank, where the total flow volume had dropped to about 50 000 m^3, a 98% reduction over 57 km, or 1.7% km^{-1}. The peak discharge exhibited a similar decay, dropping from 159 m^3 s^{-1} at Greylingshof, to 52 m^3 s^{-1} at Gobabeb, a 67% reduction over 140 km, or 0.48% km^{-1}. A recurrence interval of about 2.6 years was calculated for this flood at the Gobabeb gauge, based on the annual peak discharge series (n = 17). From Gobabeb to Rooibank, peak discharge dropped from 52 m^3 s^{-1} to about 1 m^3 s^{-1}, a 98% reduction over 57 km, or 1.7% km^{-1}. These estimates are similar to values calculated from an analysis of the annual flow record (n = 14) for the three stations, which also indicate that transmission losses from the Kuiseb–Gaub confluence average about 52% (SD = 21%) and losses between the Gobabeb and Rooibank gauges average around 86% (SD = 12%) (Jacobson, 1997). Flow velocity at peak discharge dropped from 2.2 m s^{-1} at Greylingshof to 2.0 m s^{-1} at Homeb, 110 km downstream. From Homeb to Rooibank, a distance of 90 km, peak flow velocity dropped to 0.8 m s^{-1}.

Floodwater analysis

Floodwaters transported high concentrations of total suspended sediments (TSS) at peak discharge, with a mean value of 35.3 g L^{-1} (SD = 20.6, n = 20). The highest value measured was 139.7 g L^{-1} from a bore sample collected at Swartbank, while the lowest was 0.016 g L^{-1} from a recession flow (< 1 m^3 s^{-1}) sample collected at Greylingshof. Peak TSS values were associated with flood bores travelling between Gobabeb and Swartbank, and a downstream increase in concentration was observed among the sampling sites. A downstream increase in TSS values from Greylingshof to Gobabeb was also observed in the January 1994 flood, although a significant decrease occurred from Gobabeb downstream to Rooibank (Table 2). Fine particulate organic matter (FPOM) contributed an average of 11.8% (SD = 2.7, n = 20) of the total suspended sediments collected during discharge peaks, increasing to 39.8% (SD = 3.1, n = 12) during recession flows less than 1 m^3 s^{-1}. Samples collected from bores were similar to those at peak discharge, averaging 13.9% (SD = 4.1, n = 17).

FPOM ranged from 0.014 g L^{-1} in a recession flow sample (< 1 m^3 s^{-1}), to 22.1 g L^{-1} in a bore sample collected at Swartbank during the first flood of 1993. FPOM averaged 4.17 g L^{-1} (SD = 2.50, n = 17) in

Table 2 Variation in water chemistry characteristics among sites along the lower Kuiseb River. Samples were collected during the peak discharge at each site during a 2-day flood in January 1994

Site	km	Discharge ($m^3 s^{-1}$)	DOM ($g L^{-1}$)	POM ($g L^{-1}$)	DOM/POM	TSS ($g L^{-1}$)
Greylingshof	0	159	0.0390 (0.005)	0.78 (0.06)	0.050	11.8 (0.9)
Homeb	105	–	0.0557 (0.014)	1.90 (0.06)	0.029	30.3 (5.7)
Gobabeb	140	51	0.0492 (0.014)	3.24 (0.90)	0.015	48.0 (12.3)
Rooibank	197	< 1	0.0831 (0.013)	2.36 (0.32)	0.035	19.7 (1.7)

Standard deviation is indicated in parentheses (n = 3). Distance downstream from Greylingshof is indicated in kilometres. Discharge was not determined at Homeb.

samples collected during peak discharge. The concentration tended to increase downstream, as reflected in samples collected during the January 1994 flood (Table 2). Levels of dissolved organic matter (DOM) were significantly lower, averaging 0.082 $g L^{-1}$ (SD = 43.5, n = 17) during peak discharge. DOM concentrations ranged from 0.0056 $g L^{-1}$ in a recession flow (< 1 $m^3 s^{-1}$) sample collected at Greylingshof, to 0.228 $g L^{-1}$ in a bore sample collected at Swartbank during the first flood of 1993. DOM concentration did not exhibit any distinct downstream trend, excluding a small increase observed from Gobabeb to Rooibank in the January 1994 flood. The ratio of DOM to POM averaged 0.024 (SD = 0.025, n = 17) in samples collected during peak discharge. This ratio did not differ from that of bore samples, which averaged 0.023 (SD = 0.021, n = 17). However, the ratio increased significantly in samples collected during the final stages of flood recession (< 1 $m^3 s^{-1}$) averaging 0.450 (SD = 0.332, n = 12). The proportion of POM in the organic load transported by the January 1994 flood increased markedly between Greylingshof and Gobabeb and then decreased downstream to Rooibank (Table 2).

Integration of the discharge and concentration data for the January 1994 flood revealed a marked downstream decrease in the total transport of organic matter in association with the reduction in flow volume (Table 3). While 3338 metric tons were exported out of the escarpment into the lower river, only 106 tons were transported past Rooibank (Table 3). However, while flow volume and DOM mass exhibited 48.4 and 55.0% reductions, respectively, between Greylingshof and Gobabeb, the mass of POM increased 48.7% to 4610 tons. The greatest change occurred between Gobabeb and Rooibank; flow volume, and DOM and POM mass were reduced ≈ 98% over this 58 km reach. TSS transport increased from 24 110 to 46 300 tons between the escarpment and Gobabeb, followed by a 98% reduction between Gobabeb and Rooibank. The organic proportion of the TSS ranged from 10.0% to 12.9% from the escarpment to Rooibank (Table 3).

The concentration of CPOM (> 1 mm) in a flood bore varied as it travelled downstream, increasing from 137.0 to 181.4 $g L^{-1}$ between Homeb and Swartbank, followed by a sharp decline to 12.6 $g L^{-1}$ at Rooibank. The lateral deposition of particulate organic matter exhibited a similar pattern among these sites (Table 4). Strandline deposits at Homeb averaged 1 344 $g m^{-2}$ (SD = 768), increasing to 11 296 (5 408) $g m^{-2}$ at Swartbank, 65 km downstream (P = 0.003). At Rooibank, another 30 km downstream, no measurable deposits were produced during flood recession. The composition of the deposits also differed; 76% of the material deposited at Homeb was larger than 1 mm, the proportion decreasing to 32% at Swartbank. The spatial extent of the deposits also varied, increasing from an average width of 30 cm (SD = 11) at Homeb to 110 cm (SD = 33) at Swartbank.

Table 3 Total water (H_2O), dissolved (DOM) and particulate organic matter (POM) and suspended solids (TSS) transported during a 2-day flood of the Kuiseb River in January 1994

Site	H_2O	DOM	POM	DOM/POM	TSS	% Organic
Escarpment	4.75	238	3 100	0.077	24 110	12.9
Gobabeb	2.30	131	4 610	0.028	46 300	10.0
Rooibank	0.05	4	102	0.039	810	12.6

Flow volume is in million cubic meters and organic matter is in metric tons; % is the proportion of TSS.

Table 4 Variation in lateral deposits (strand lines) of particulate organic matter (> 1 mm diameter) following a flood in the Kuiseb River

Site	km	Dry weight (g m^{-2})	> 1 mm (%)
Homeb	0	1 344 (768)	76 (4)
Gobabeb	25	3 200 (1 696)	39 (7)
Swartbank	65	11 296 (5 408)	32 (11)
Rooibank	95	0	0

Standard deviation is indicated in parentheses (n = 4). Distance downstream from Homeb is given in kilometres. The Gobabeb site is 12 km upstream of the Gobabeb gauge.

Floodwater pH averaged 7.29 (SD = 0.05, n = 20) for samples collected at peak discharge, ranging from a low of 6.70 in a bore sample at Schlesien to 8.00 for a recession flow (< 1 m^3 s^{-1}) sample at Gobabeb (Table 5). The pH of bore samples was slightly lower, averaging 7.13 (SD = 0.06, n = 17), while pH tended to increase during recession, averaging 7.68 (SD = 0.19, n = 12). Low bore pH was associated with high POM levels, and organic acids may have contributed to the decrease in pH.

Conductivity also varied among bore, peak, and recession samples, as well as exhibiting a downstream increase (Table 5). Conductivity averaged 620 μS cm^{-1} (SD = 185, n = 20) in peak discharge samples, increasing to 815 μS cm^{-1} (SD = 251, n = 17) in bore samples. In contrast, recession flow (< 1 m^3 s^{-1}) samples averaged 294 μS cm^{-1} (SD = 107, n = 12). The highest values were consistently recorded at Rooibank, where a bore sample measured 1415 μS cm^{-1}.

Sodium, potassium, calcium, magnesium, and chloride all exhibited a downstream increase from Greylingshof to Rooibank during the January 1994 flood (Table 5). The exception to this trend was sulphate with no distinct change among the sites. Sodium and chloride exhibited the most dramatic change with five-fold increase from Greylingshof to Rooibank. Alkalinity also increased downstream, more than doubling between Greylingshof and Rooibank (Table 5).

Discussion

Hydrological controls of transport and deposition

The composition, transport, and deposition patterns of materials carried in Kuiseb River floodwaters clearly diverges from those characteristic of more mesic systems, and much of this variation is attributable to downstream hydrological decay. Termination of floods within the river's lower 100 km renders the reach a sink for materials exported from upstream. Vogel (1989) observed such localised deposition, noting that the Namib's rivers deposit their inorganic sediment load along a stretch of riverbed corresponding to the average reach of their floods, resulting in a convex deviation in the river's longitudinal profile near the coast. Our observations were similar as deposition patterns corresponded with the convexity observed in the lower reaches of the Kuiseb's longitudinal profile (Jacobson *et al.*, 2000).

While TSS levels varied in response to hydrological decay, the organic proportion of TSS remained comparatively constant, averaging 11.8%. POM in rivers is often expressed as a percentage of the TSS, and values from the world's rivers range from 1.3 to 8.4%, with POM and TSS concentrations ranging from 0.6 to 14.2 mg L^{-1} and 5–1500 mg L^{-1}, respectively (Ittekkot & Laane, 1991). The relative proportions of organic matter within suspended sediment samples from dryland rivers are at or beyond the upper end of this range. Suspended solids peaked at 55.2 g L^{-1} in a flash food in Sycamore Creek, and the organic fraction of the sediment load ranged from 9 to 13% (mean = 11%) (Fisher & Minckley, 1978). Similarly, Sykes (1937) reported that sediments deposited in the Colorado River delta were ≈ 8% organic matter (by weight).

Table 5 Variation in water chemistry characteristics among sites along the lower Kuiseb River. Samples were collected during the peak discharge at each site during a 2-day flood in January 1994

Site	Conductivity (μS cm^{-1})	pH	Alkalinity (mg L^{-1})	Na	K	Ca	Mg	Cl	SO_4
Greylingshof	302 (69)	7.33 (0.06)	166 (2)	11 (3)	9 (1)	156 (22)	34 (2)	17 (6)	18 (5)
Homeb	627 (38)	7.13 (0.06)	290 (30)	26 (3)	20 (6)	229 (14)	55 (7)	38 (4)	9 (5)
Gobabeb	703 (72)	7.43 (0.21)	354 (117)	29 (8)	24 (7)	280 (93)	70 (21)	41 (10)	6 (8)
Rooibank	1 035 (252)	7.30 (0.10)	373 (90)	60 (3)	21 (3)	282 (98)	70 (14)	79 (14)	11 (11)

Standard deviation is indicated in parentheses (n = 3). Ion concentrations are in parts per million.

Organic matter transport and deposition exhibited patterns similar to those observed for inorganic sediments. Jacobson *et al.* (1999b) recorded a downstream increase in the retention of woody debris in the Kuiseb River, largely attributable to hydrological decay. The deposition patterns of fine particulate organic matter (FPOM) are similar, with the bulk of transported FPOM deposited within the lower river in response to hydrological decay.

The hydrological decay and associated increase in retention also results in downstream sorting of the organic load. The decline in stream power associated with the hydrological decay (Jacobson *et al.*, 1999b) caused the percentage of large organic particles in transport to decrease downstream. The principal deposition zone for woody debris was the 80-km reach immediately upstream of the Gobabeb gauge (Jacobson *et al.*, 1999b), while that for FPOM occurred in the 50-km reach downstream to the Rooibank gauge.

The concentration and composition of the dissolved load also varied along the channel network, with a significant downstream increase in the concentration of many ions. This increase in inorganic solute concentration is associated with an increase in the salinity of alluvial soils within the lower reaches of the Kuiseb River (Jacobson *et al.*, 2000). Such increases can also negatively impact downstream water quality in ephemeral systems (Sharma *et al.*, 1984a).

Interannual hydrological variation will shift the position of deposition zones for dissolved and particulate material, both organic and inorganic. The positions within the channel network will vary with flood magnitude, shifting upstream or downstream with decreases or increases, respectively (Jacobson *et al.*, 1999b). When this interannual variability is averaged over many years, a mean deposition zone for transported materials can be defined in relation to the 'average reach of the floods', as noted by Vogel (1989). The spatial and temporal extent of such accumulations within ephemeral systems is thus directly dependent on the dynamics of the hydrological regime.

Organic load dynamics

The largest component of organic loading in streams is in the dissolved state (Moeller *et al.*, 1979; Thurman, 1985; Allan, 1995), although the ratio of DOM to POM has been found to vary from 0.09 to 70 (Moeller *et al.*, 1979). Reports of POM contribution to total annual organic export range from 4% for the Ogeechee River, a blackwater river in Georgia, to 77% for Bear Brook, a 2nd-order stream in the White Mountains of New Hampshire (Golladay, 1997). Values recorded in the Kuiseb River are thus among the highest yet reported, with POM constituting ≈ 97% of the total organic load. Jones *et al.* (1997) report a similar figure for Sycamore Creek within the Sonoran Desert, estimating that POM represented 98.3% of the total annual carbon exports.

Despite the predominance of particulate matter, the Kuiseb River transports high concentrations of both dissolved and particulate organic matter during floods, and both often exhibit a downstream increase. Average total organic matter (TOM) levels during flow in the Kuiseb River were in excess of 4000 mg L^{-1}. This value is again similar to observations from Sycamore Creek, where floodwater samples contained an average TOM in excess of 4000 mg L^{-1} (Jones *et al.*, 1997). In contrast, Mulholland & Watts (1982) reported total organic matter (TOM) concentrations for streams throughout North America ranged from 3.2 to 43.4 mg L^{-1}, although these figures may not all be directly comparable to the spate-flow conditions which typify discharge in ephemeral systems.

Downstream increases in FPOM within the Kuiseb River are attributable to both hydrological decay and local contributions of organic matter from the riparian forest along the lower reaches of the river. Organic matter accumulates in the channel and floodplain during the dry season and is flushed downstream in the next flood. Nonetheless, FPOM may not drop significantly in subsequent floods. While antecedent storms may greatly deplete transportable materials in dryland catchments (Fisher & Grimm, 1985), the high temporal and spatial variability of precipitation, combined with the large size of the Kuiseb catchment, may limit the extent to which such depletion is observed as source areas for individual floods vary across the catchment.

Primary production and decomposition rates influence the amount of DOM in water, and accordingly, arid environments have been thought to have inherently low DOM concentrations (Thurman, 1985). However, riparian vegetation can deliver large amounts of organic matter to ephemeral river channels. In conjunction with low decomposition rates during interflood periods, large accumulations may accrue, yielding high DOM levels when surface flow resumes. *Faidherbia* fruits may be an important source of DOM within the lower reaches of the Kuiseb River. The highest DOM levels observed during the study (up to 228 mg L^{-1}) were measured in the lower river (near Swartbank) during the first flood of the season, which flushed accumulated *Faidherbia* fruits downstream. Leaching experiments with fresh plant litter have shown that up to 40% of the organic matter of the plant may be dissolved in 24 h (Thurman, 1985). Soluble carbohydrates and polyphenols are the principal constituents lost during leaching (Suberkropp, Godshalk & Klug, 1976), and these materials make up more than 50% of the dry mass of *Faidherbia* fruits (Wood, 1989).

In addition to the downstream increase in allochthonous loading, the amount of material leached from organic matter increases with time in solution (Suberkropp *et al.*, 1976). Thus, as floods travel downstream transporting their load of organic particulates, DOM gradually increases. While the spatial variability of DOM concentration among catchments reveals no general trend (Sedell & Dahm, 1990), we believe the downstream DOM increase in the Kuiseb River may be an inherent feature of ephemeral rivers.

The DOM concentrations measured in lower Kuiseb River are among the highest reported from any aquatic system. Ranging from 5.6 to 228 mg L^{-1}, with an average of 82 mg L^{-1} at peak discharge, they greatly exceed the estimated global average of 10 mg L^{-1} for streams and rivers (Meybeck, 1982). While interflood accumulations of fresh, carbohydrate-rich organic matter contribute to these high levels, physical processing associated with fluvial transport in a warm (30–32 °C), abrasive, and turbulent environment must facilitate rapid leaching of soluble organic material. The highest DOM levels recorded in the Kuiseb River were measured in flood bores within the lower reaches of the river. These turbulent bores carry the highest levels of particulate organic matter recorded, and may advance for 1–3 days over distances of several hundred kilometres at water temperatures of 30–32 °C, with continual additions of unleached organic matter. Comparable DOM concentrations were recorded in the vicinity of the Mt St Helens volcanic blast zone in south-western Washington, U.S.A. (Baross *et al.*, 1982). Cold (10 °C), oligotrophic aquatic environments were temporarily transformed into warm (34 °C), organic-rich environments after receiving massive inputs of wood debris and pyrolised soluble organics from adjacent destroyed forests, generating DOM levels near 100 mg L^{-1}.

Blackwater rivers and streams have provided the highest levels of DOM measured within unaltered perennial systems, with average DOM concentrations up to 30 mg L^{-1} (Meyer, 1986). Although much of this material consisted of refractory high molecular-weight fractions, a significant proportion (10–20%) was low molecular-weight and presumably highly labile. Such labile organic matter provides an important energy source for the microbial component of the food web within blackwater rivers and streams (Meyer, 1990). Given the limited decomposition that occurs between floods in drylands, an even larger percentage of the DOM in ephemeral rivers may be labile, although it largely fuels heterotrophic respiration by terrestrial communities rather than their aquatic counterparts.

Mulholland (1997) suggested that the comparatively high DOM levels reported from dryland streams may be attributable to catchment characteristics, including lower mineralisation rates, limited sorption of DOM in sandy soils, and rapid delivery of water from the catchment to the channel. As a result, dryland catchments may export a significantly larger proportion of their annual primary production as DOM and POM relative to more mesic catchments (Mulholland, 1997). Such export may have important implications for downstream heterotrophic communities in ephemeral rivers such as the Kuiseb.

A key issue regarding the organic matter dynamics of rivers and streams concerns the extent of in-stream processing occurring relative to downstream export. Opportunities for such processing are directly linked to the stream's ability to temporarily store organic carbon within the channel (i.e. their retentiveness) (Maser & Sedell, 1994; Webster *et al.*, 1994). Ephemeral rivers such as the Kuiseb are an extreme example where retentive structures, in combination with hydrological decay, often result in no export from a reach or the system as a whole. In the Kuiseb River, the deposition zone within the river's lower reaches functions as a sink for fluvially transported organic matter. The large amount of organic matter deposited in the lower reaches of the river is an important carbon source for flood-activated heterotrophs, including fungi and invertebrates (Shelley & Crawford, 1996; Jacobson *et al.*, 1999a, b, 2000). Thus, we suggest that the influence of hydrological variability on the distribution and composition of fluvially transported organic matter, and hence, on the structure and distribution of downstream heterotrophic communities, is a feature common to all fluvial ecosystems, irrespective of their hydrological regime.

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