Dust activity and surface sediment characteristics of the dustiest river in southern Africa: the Kuiseb River, Central Namib

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ABSTRACT

Previous remote sensing studies (2005–2008) have identified Namibia's Kuiseb as the dustiest river in southern Africa. The purpose of this study was to extend the dust event record through to 2014, and to examine the nature of the surfaces from which this satellite imagery indicates these dust plumes originate. The new 10-year record confirms the delta as the dustiest geomorphological unit (54% of plumes), followed by the gravel plain (28%) and then the river (8%). No dust originated from the Namib Sand Sea dunes or interdunes. Field observations provided detail about the geomorphological and sedimentological setting of the landscape components. The laboratory analysis focused on the size characteristics of 153 surface sediment samples collected from the Kuiseb main channel, its terraces, delta, gravel plain surfaces and tributaries, dunes and interdune. This study has identified that surface sediments suitable for dust production increase towards the coast with particular 'dusty' floodplain surfaces between Swartbank and Rooibank and the Kuiseb delta. We suggest that silt crusts formed as the flood water dissipate, provide a main source of potentially entrainable material for emission. The crusts consist entirely of silt- and clay-sized materials, with a maximum of 97% <63 μm, 39% <10 μm and 6% <2 μm. Anthropogenic disturbances of the surfaces are potentially playing a role in the production of dust, with the area undergoing significant development.

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MODIS; Namib Desert; geomorphology; particle size distribution; anthropogenic modification

Introduction

Aeolian dust has significant impacts on the earth's systems, depending on the physico-chemical properties of the dust such as size distribution, shape and composition (Formenti et al., 2011; Mahowald et al., 2014). These impacts include significant influences on the biogeochemical cycles of the ocean and terrestrial systems (Xuan & Sokolik, 2002). It has been demonstrated that atmospheric iron-rich micro-nutrient dust may drive marine phytoplankton activity (Martin & Fitzwater, 1988; McTainsh & Strong, 2007) and provide nutrients to fynbos of the Cape Floristic Region in South Africa (Soderberg & Compton, 2007). Aeolian dust could also influence soil integrity,

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development and fertility at both the source and sink regions (Bullard et al., 2011). The <10-µm dust has the ability to scatter and absorb solar and infrared radiation and hence has an influence on the earth's energy budget and climate (Xuan & Sokolik, 2002). The <10-µm fraction can also have adverse effects on people's health, in particular causing respiratory ailments and infections and cardiovascular events (Chen et al., 2010; Griffin & Kellogg, 2004; Kanatani et al., 2010).

Prospero, Ginoux, Torres, Nicholson, and Gill (2002) maintain that most of the world's dust emission sources are situated in topographic lows of arid regions subject to surface water activity. Such internally draining environments, with low-energy flow, conducive to the deposition of sediments have been identified as dust emitters in many parts of the world (Koven & Fung, 2008). The dominant sources are terminal deltas, lakes and dune fields replenished by past fluvial sediment deposition or contemporary ephemeral processes, such as in the Lake Eyre and Murray–Darling Basins in Australia (Bullard & McTainsh, 2003), the inland Niger River delta in Mali (McTainsh, Nickling, & Lynch, 1997), the Heihe River in north-western China (Wang, Wanquan, & Mingyuan, 2004), the Owens River draining into Owen (dry) Lake in California (Cahill, Gill, Reid, Gearhart, & Gillette, 1996) and the ephemeral channels draining into Etosha Pan (Bryant, 2003). Such source regions consist of varied geomorphological units with a wide range of surface characteristics that are both dynamic and complex. The majority of dust sources produce dust on an intermittent basis, when supply of appropriate sediment is available for deflation and wind energy is sufficient to entrain the sediment.

In southern Africa, the major dust sources include the Etosha and Makgadikgadi pan complexes and the Namib Desert, with dust originating mainly from the ephemeral rivers and coastal pans (Eckardt & Kuring, 2005; Vickery, Eckardt, & Bryant, 2013). All 12 major westward flowing ephemeral rivers originating in the highlands produce dust. Remote sensing observations suggest that the Kuiseb River is one of the dustiest rivers in southern Africa (Vickery & Eckardt, 2013). The dustiness of this river has been attributed to the summer floods which originate in the headwaters situated in the Khomas Hochland and terminate in the lower Kuiseb River. As water dissipates, large amounts of silt-sized sediments are deposited in the lower sections of the river (Jacobson, Jacobson, Angermeier, & Cherry, 2000a, 2000b), which has been suggested to be the dominant source of the dust produced during high-magnitude winds that occur in winter (Eckardt & Kuring, 2005).

The influence of people on the basin cannot be discounted. Water extraction and diversions schemes in the lower Kuiseb have been in place for decades (Dausab et al., 1994). Livestock is present along the entire length of the lower Kuiseb River (Henschel & Parr, 2010). Exploration and mining licences cover the gravel plain areas (http://portals.flexicadastre.com/Namibia/) of the Namib–Naukluft Park. Numerous quarries and extensive exploration scrapes are clearly visible on Google Earth. The proliferation of roads to access the infrastructure within the area, as well as off-road vehicles have also disturbed the landscape. Such activities have the ability to alter the surface characteristics of the area (McTainsh et al., 1997; Zobeck, Baddock, & Van Pelt, 2013).

The Kuiseb region comprises a variety of geomorphological units and surface characteristics, many of which are associated with fluvial activity, both past and present. The surface characteristics play an important controlling force on dust activity and include surface moisture content; soil characteristics, including particle size distribution and mineralogy;

and roughness elements, such as vegetation and topography. Aeolian activity for this catchment has been linked to the delta (59%) and the lower Kuiseb River and its tributaries (41%) with the aid of MODIS satellite imagery from 2005 to 2008 (Vickery & Eckardt, 2013). No dust activity was detected from the gravel plain stone pavements to the north or the sand dunes to the south for the Vickery and Eckardt (2013) study. The aim of the present study is to extend the existing time-series of daily dust events captured with MODIS through to 2014 and link these dust events to surface source types within the Kuiseb catchment. Finally, to provide a detailed assessment of the particle size characteristics of the different geomorphological units that represent the dust sources identified with MODIS imagery within the Kuiseb catchment.

Study area

The headwaters of the Kuiseb River are situated in the Khomas Hochland Mountains just to the west of Windhoek at approximately 2000 m.a.s.l. (Figure 1). The rainfall in the headwaters (250–350 mm/year) generates the floods that flow 440 km through the Namib Desert eastward towards the coast. The river cuts through the escarpment and enters the Kuiseb River Canyon which can be up to 200 m deep and 35 m wide (Morin et al., 2009) dominated by schists. From the end of the canyon, 100 km from the coast, the river morphology changes to a sandy alluvial channel and rainfall drops significantly from approximately 150 mm/year at the top of the canyon to <25 mm/year near the delta (Eckardt et al., 2013). The lower Kuiseb River has often been described as a linear oasis, with lush riparian vegetation situated within the river channel and/or on the floodplain (Huntley, 1985). The aquifer situated within the alluvium of the Kuiseb River sustains vegetation along the course of the river in this otherwise arid environment of the Namib Desert. The floods have reached the Atlantic Ocean, only 18 times in the last 180 years (data from Gobabeb Research Station, Morin et al., 2009). The major geomorphological units of the lower Kuiseb are comprised of the main river, including the channel and floodplains (of various ages); the delta; the gravel plain; and Sand Sea, including dune fields and interdune areas.

The lower river can be divided into three main sections based on river morphology and vegetation (Huntley, 1985; Theron, Van Rooyen, Van Rooyen, & Jankowitz, 1985). The upper riverine woodland section stretches from Harubes, where the Gaub River flows into the Kuiseb, to approximately Soutrivier. The middle riverine woodland section stretches from Soutrivier to Swartbank and the lower riverine woodland section stretches from Swartbank to Rooibank. The river exits the incised canyon in the upper section where it enters the low relief desert plains and becomes increasingly wider, braided and more sparsely vegetated as it flows through the middle to lower sections. The dust activity associated with the river as identified previously with MODIS (Vickery & Eckardt, 2013) starts at around Homeb (Figure 1), where the canyon becomes shallow (<10 m).

A few kilometres downstream of Rooibank the river enters the delta and channel splits in two. The southern channel meanders through coastal sand dunes towards the Atlantic Ocean, while the northern channel has been blocked from traversing the delta since 1962 to protect Walvis Bay from flooding (Jacobson, Jacobson, & Seely, 1995). The lower reaches of the river are bordered by the Namib Sand Sea to the south, which has been slowly encroaching northwards, during the Quaternary (Ward, 1987). The large dunes are prevented from

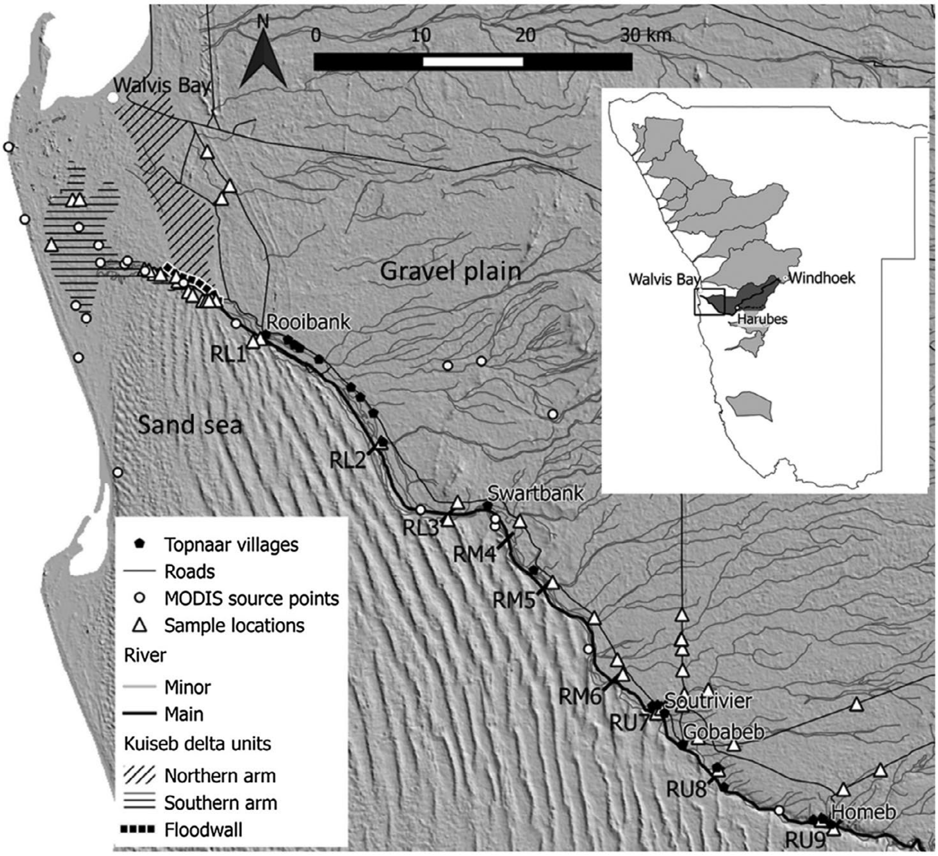

Figure 1. The lower Kuiseb catchment study site with sample locations as part of this study and MODIS source points as per Vickery and Eckardt (2013). The Kuiseb River delta used to consist of two arms (Northern and Southern) where the water used to flow through. A floodwall built in 1962, blocked off the northern arm to prevent flooding in the Walvis Bay. When the river floods reach the delta area, only the southern arm presently receives flowing water. The main river channel sections are as follows: RL – lower river from Rooibank to Swartbank, RM – middle river from Swartbank to Soutrivier and RU – upper river from Soutrivier to Harubes. The minor Gaub river flows into the Kuiseb River where the river is still confined to the canyon (shorter channel to the south shown in the small inset, dotted line). River catchments in small inset from Jacobson et al., 1995. Topography from shaded ASTER GDEM version 1.

crossing the river by the scouring action of the floods but their sands are deposited downstream in the widening channel and delta.

To the north of the river lies the rock desert or gravel plain, a low gradient (1%) surface composed of gypcrete, calcrete and uncemented sediments, variably covered by gravel (Eckardt & Spiro, 1999). It has been proposed that these stone pavements form by the accumulation of dust that result in the upward growth of the soil profile (McFadden, 2013). The stone pavement is intersected by ephemeral channels with several playas situated within the drainage network (Eckardt, Drake, Goudie, White, & Viles, 2001). Although stone pavements are generally not regarded as dust sources due to the protection afforded by the gravel armouring (Sweeney, McDonald, & Etyemezian, 2011), research have pointed to the fact that the dust emission potential from such surfaces could be significant

(Wang et al., 2012; Xuan & Sokolik, 2002). Wang et al., 2012 tested Gobi Desert stone pavements in a wind tunnel and concluded that they are potentially important sources of aeolian dust.

Methods

MODIS data

MODIS true colour imagery from both the Terra and Aqua sensors were used to extend the 2005–2008 dust event record of Vickery and Eckardt (2013) up to 2014. Images from January 2009 to May 2012 were obtained from the NASA Rapidfire online facility (http://lance-modis.eos- dis.nasa.gov/imagery/subsets/?subset = Namibia), followed by NASA worldview up to 2014 (https://worldview.earthdata.nasa.gov). The source of each dust plume was identified as a point where its origin could be unambiguously placed in one of the geomorphological units within the lower Kuiseb catchment. Plumes for which the source could not be determined were classified as uncertain. An example of a dust event for the study area captured by MODIS is given in Figure 2.

Wind speed data

Era-Interim 10 metre wind speed data for the same period was used to compare the MODIS dust event frequency to high-magnitude north-easterly wind events for the same area (Dee et al., 2011). Wind speeds of 6 ms^{-1} and greater were regarded as high magnitude wind events (von Holdt, Eckardt, Wiggs, in press). These data were downloaded at a resolution of

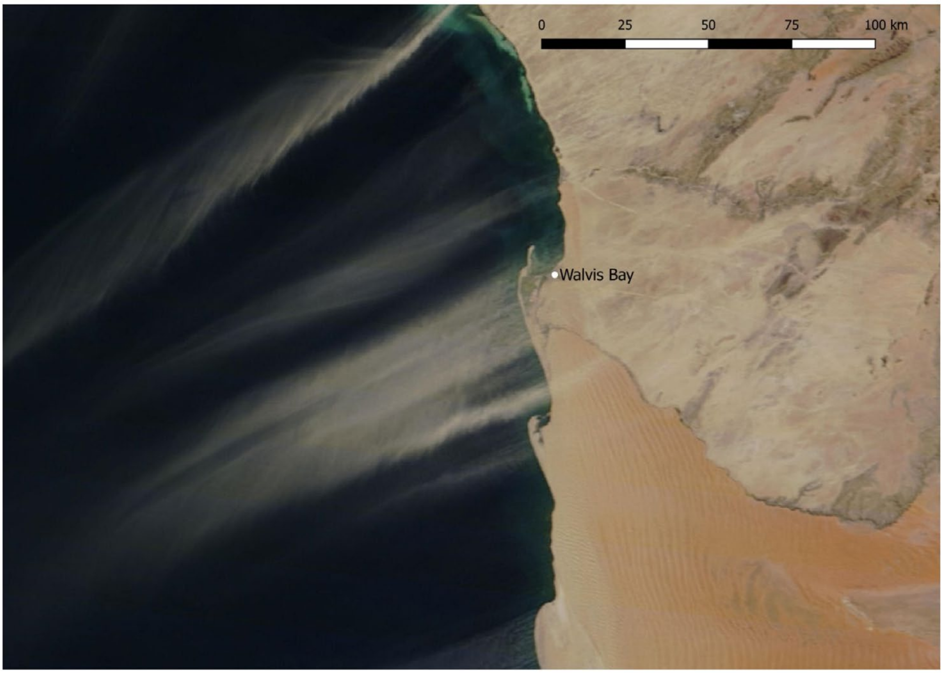

Figure 2. Dust event for the Central Namib captured by the MODIS Terra sensor for 17 June 2010 (Julian day 2010168).

0.125° for every six-hourly time step. The mean across latitude and longitude was calculated using Climate Data Operators (CDO) software v1.7.2 (http://www.mpimet.mpg.de/cdo), followed by the wind speed from corrected u10 and v10 components.

Sampling and analysis

To assess the sediment characteristics and dust emission potential of the study area, surface samples from the major geomorphological surface units of the lower Kuiseb catchment area, both dust and non-dust producing were obtained. The units included the river, consisting of both the main channel and floodplain; the delta; the gravel plain and limited samples from the Sand Sea dune fields and interdune areas (Table 1). The choice of sampling sites was guided by the source points identified with the aid of MODIS true colour images for the period from 2005 to 2008 by Vickery and Eckardt (2013) and for 2009–2011 for the current study. Sampling took place in September 2012 and March 2013. Samples along the river were taken in the upper (RU), middle (RM) and lower river (RL) sections along nine transects (labelled RL1-3, RM4-6, RU7-9 in Figure 1). Generalized cross sections of all the main geomorphological units included in this study are given in Figure 3.

The particle size analysis of 153 surface sediment samples was done by laser diffraction on a Malvern Mastersizer 2000 attached to a Hydro 2000G wet sample dispersion unit with tap water as dispersant. Selected samples from each major geomorphological unit were further investigated with SEM/EDS (Nova Nanosem 230) to determine particle morphology and elemental composition. A cluster analysis was conducted based on the percentage of <10 μm and <63 μm to explore possible source areas and trends present. These two size categories were chosen as the clay and silt (<63 μm) traditionally represent important dust fractions for long-term dust particle suspension (Bagnold, 1941; Gillies, 2013; IPCC, 2013). The size of suspended particles will vary with the velocity of the wind and particles of more than 100 μm have been sampled 1000s of kilometres from the African coast (van der Does, Korte, Munday, Brummer, & Stuut, 2016). However, for this ground-based analysis it was decided to focus on the most likely particle sizes identified thus far for regional and global deposition (Lawrence & Neff, 2009). The clustering was done using Ward's method of hierarchical tree clustering, using the Euclidean distance as the measure of distance. Clusters were determined using Statistica statistical software. All geographic coordinates for samples and particle size analysis results are included in the supplementary section.

Table 1. Geomorphological units sampled and relevant codes.

Unit	Code	Segment
River	RU	Upper river floodplain: comprising the most upstream section of the lower Kuiseb River. From the Canyon to Soutrivier
	RM	Middle river floodplain: from Soutrivier to Swartbank
	RL	Lower river floodplain: comprising the most downstream section of the river before is opens up into the detla. From Swartbank to Rooibank
	RAC	River active channel
Delta	DAC	Delta active channel sand
	DCC	Delta channel depositional crust
	DFP	Delta floodplain
Gravel plain	GPC	Depositional crust in the drainage network channels of the gravel plain
	GPS	Stone pavement with gravel overlay
Sand Sea	SS	Sand Sea sand
	ID	Interdune sediment

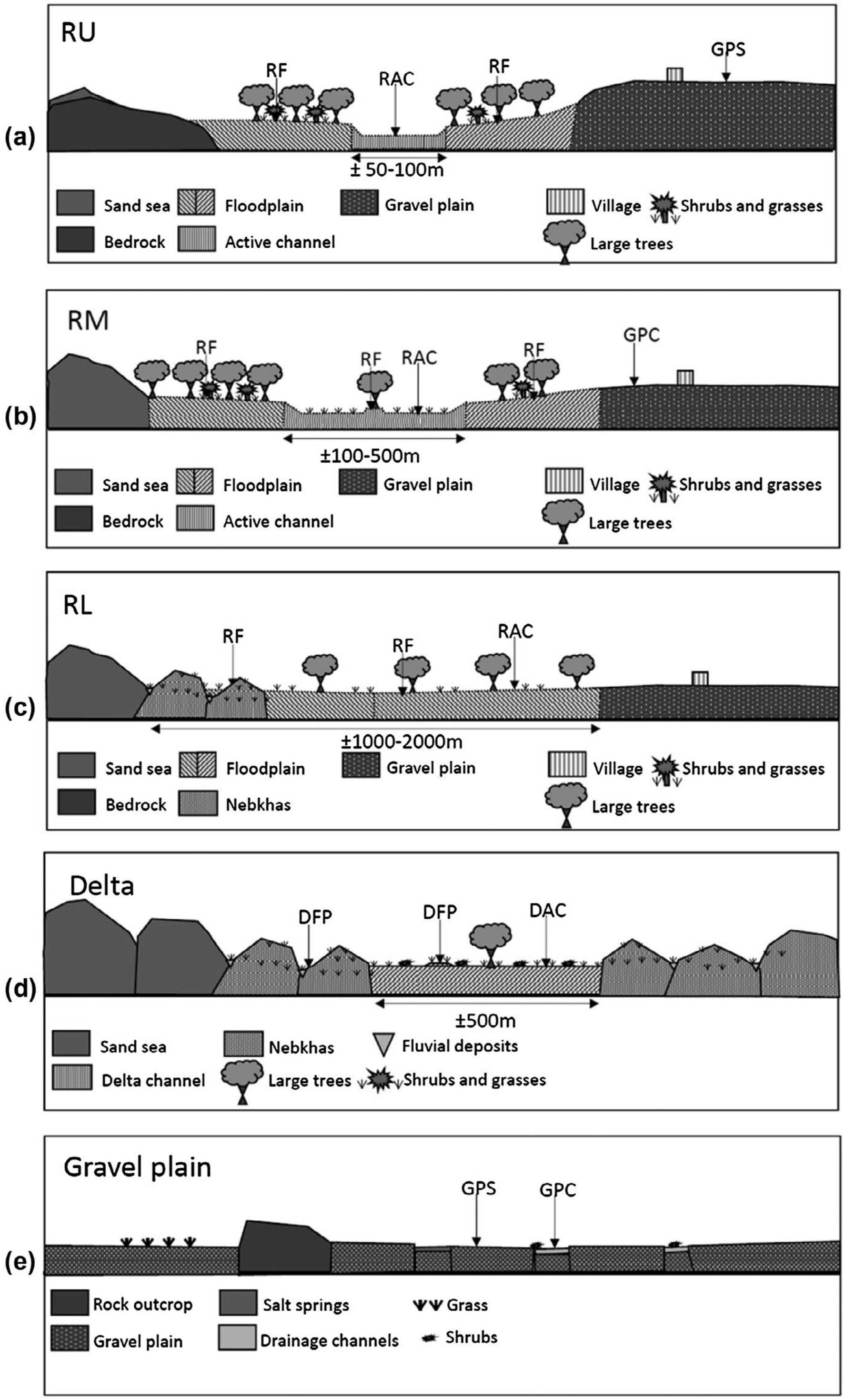

Figure 3. Generalized cross sections of geomorphological units included in this study.

Results and discussion

Extended MODIS record

The extended MODIS record for the Kuiseb River dust event days and the number of high-magnitude north-easterly wind events (>6 ms^{-1}) are shown in Figure 4(a). There appears to be no significant increase or decrease in the overall dustiness of the Kuiseb River over the 10-year study period. The number of dust events are moderately associated ($R^2 = .5$) with the number of high-magnitude wind events that occur in the basin (Figure 4(c)), indicating that there are other controls on dust emission. The geomorphologic units responsible for dust (Figure 4(b)) in the extended record are not the same as the 2005–2008 study undertaken by Vickery and Eckardt (2013), which identified the river and tributaries (41%) and delta (59%) as major source areas. This study attributes additional dust activity to the gravel plain (28% for this study versus no distinction being made between main river channel and tributaries situated in the gravel plain areas for Vickery and Eckardt (2013). The proportion of dust produced within the delta remains largely unchanged at 54% (59% previously), whereas the river only produces 8% of the plumes. The reason for this reduction is a combination of factors: the important distinction being made between the main river channel and gravel plain tributaries or wadis. This distinction was made in Vickery (2010), where the main river channel accounted for 27% of the plumes (8% for the present study) and the tributaries only 14% (28% for present study incorporated into gravel plain category). In addition, the inclusion of an uncertain category in the classification as many of the images are not clear enough to pinpoint a source and the subjective nature of selecting an origin point at a resolution of 250 m would further influence the source point attribution.

Particle size distributions of source region surfaces

The average particle size for each geomorphologic unit is an indication as a potential source of sediment that is readily entrainable (Figure 5) and include the floodplains of the delta (DFP), the entire lower Kuiseb River (RLFP, RMFP, RUFP) and the gravel plain crusts (GPC). In comparison, the gravel plain stone pavement (GPS) and the interdune (ID) surfaces contain much less potentially entrainable sediment for long-term suspension. Segments not considered as dust producing are the delta active channel (DAC), the river active channel (RAC) and the Sand Sea sand (SS). These non-dust producing sandy areas are, however, important sources of sand required for saltation (Cahill et al., 1996). The proximity of such sand to crusted silty fines in the lower Kuiseb River plays an important role in the dust production. Distributions of the different geomorphological units on a log scale are included in the supplementary section.

The cluster analysis produced six cluster types, of which Type 1 contains the largest quantity of the finest material (91% <63 μm) and Type 6 with 98% of the particles between 100 and 1000 μm. The cluster analysis highlights the dust source potential of the delta, the most downstream section of the river (RL) and the gravel plain channels (GPC) by the presence of Type 1 samples (Figure 6). The predominance of Type 1 samples in the delta and RL is to be expected. The downstream fining occurs as the suspended stream sediments are carried by the floodwater to the furthest reaches of the flood (Jacobson et al., 2000b). Sampling in September 2012 took place almost 16 months after the largest flood event in decades.

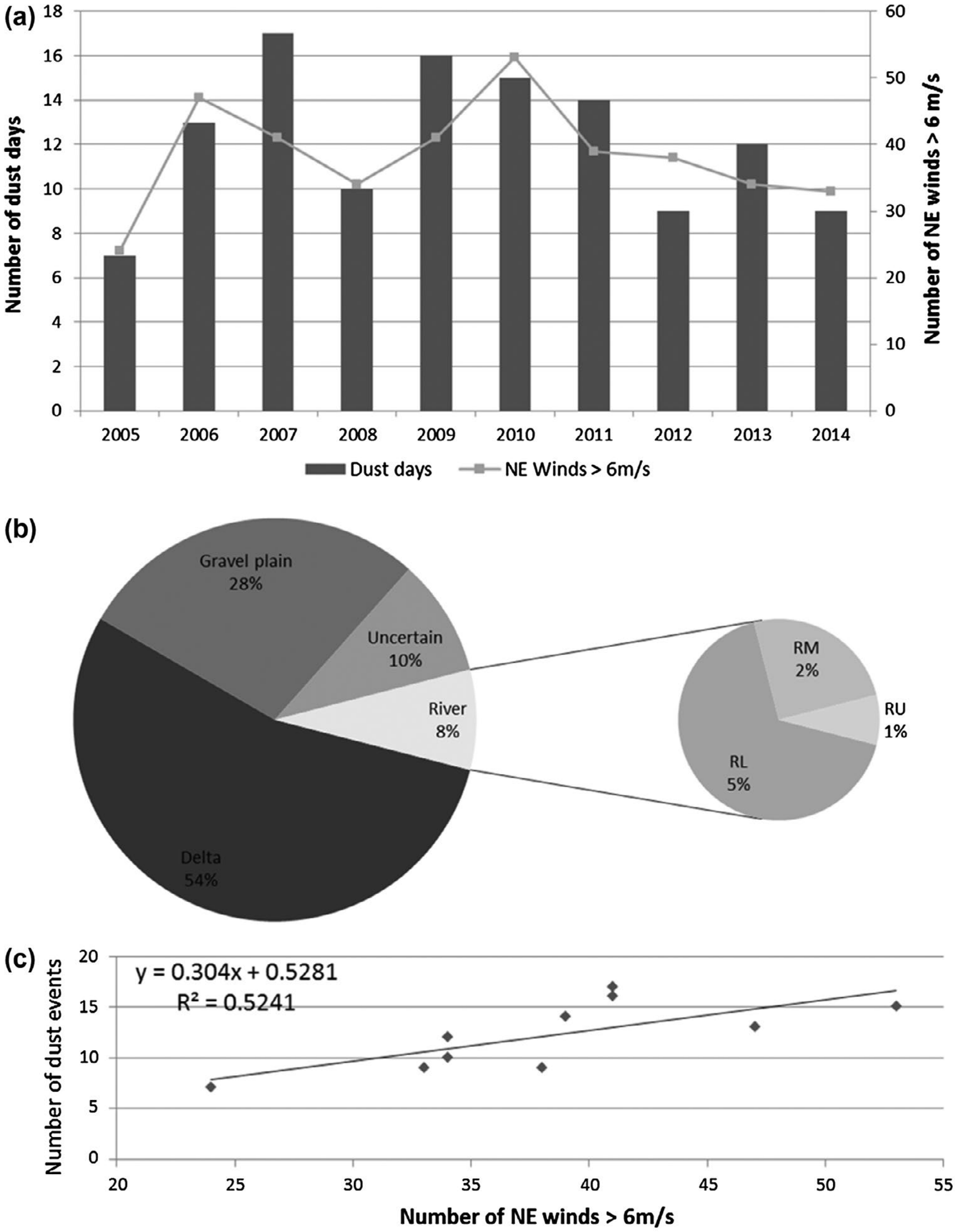

Figure 4. (a) Dust days identified with MODIS VIS composite for 2005–2014. (b) Source geomorphologies responsible for dust emission. The extended period has seen a shift in source areas compared to that identified by Vickery and Eckardt (2013) for 2005–2008: 41% from the river and 59% from the delta. The uncertain category includes poor quality images for which no source can be identified with certainty and data gaps in the data. (c) The number of dust events identified with MODIS in relation to the number of high-magnitude north-easterly wind events for the same area for each year.

The 2011 flood, which reached the Atlantic Ocean, would have carried large quantities of fine sediment into the downstream river and delta area, including fines deposited in the upstream section of the river in previous floods.

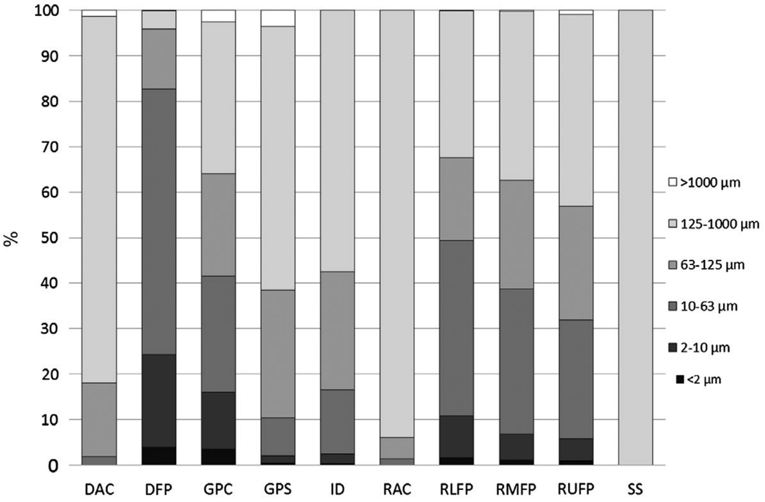

Figure 5. Average particle size analysis per geomorphological unit of the Kuiseb catchment. Codes as per Table 1: DAC – Delta active channel, DFP – Delta floodplain, GPC – gravel plain channels, GPS – gravel plain stone pavement, ID – Interdune, RAC: River active channel, RLFP – Lower river floodplain, RMFP – Middle river floodplain, RUFP – Upper river floodplain, SS – Sand Sea.

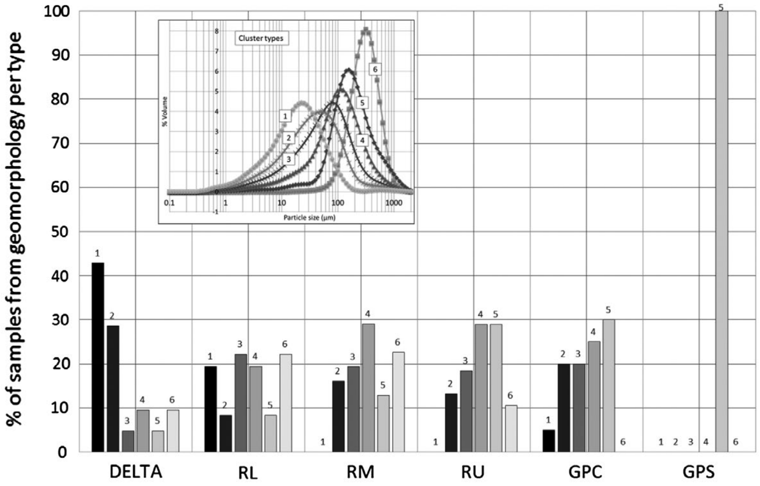

Figure 6. Summary of cluster analysis results showing the percentage of samples for each type within each unit. Delta active channel (DAC) and river active channel (RAC) merged into larger units, but active channel samples all clustered as Type 6.

The absence of Type 1 samples does not preclude a unit from being considered a potential source of dust as there are still dust-sized sediments present in cluster Types 2 to 4. Dust emission requires a supply of dust-sized particles that are available for entrainment by the wind. Source potential should also take into consideration the frequency of dust activity identified with remote sensing data. The upper river segment (RU) accounts for only 1% of the dust plumes observed with MODIS for the 10-year period from 2005 to 2014. The lack of plumes is most likely due to the density of roughness elements such as vegetation in this river segment. The valley topography, rough terrain north of river and dense vegetation (Figures 3(a) and 7(a)) results in an area of possible deposition of dust from elsewhere, rather than a supply source of dust (Okin, 2008; Wiggs, Bullard, Garvey, & Castro, 2002). This is despite the surfaces undergoing trampling by livestock in the area around Homeb and Natab, which has the highest number of livestock (43%) along the lower Kuiseb River (Henschel & Parr, 2010). It is also possible that the dust activity here has been incorrectly attributed to the river and that it in fact originates from the gravel plain to the north of the river. This is one of the drawbacks of using MODIS true colour images for dust over land at a resolution of 250 m.

In the middle segment (RM) the topography flattens out, but the vegetation remains dense as the active channel and floodplain widen and becomes partly braided (Figures 3(b) and 7(b)). Only 2% of the plumes originated in this middle section of the river. The most downstream section of the river (RL) accounts for only 5% of the plumes. This is surprising given the presence of Type 1 samples, the wide and braided nature of the river and the lack of topography (Figures 3(c) and 7(c)). This is also the most populated stretch of the river, with approximately 71% of the Kuiseb River Topnaar population residing along this segment of the river (Botelle & Kowalski, 1995). Extensive deposits of fine sediment (including Type 1) can be found in the delta fan area (Figures 3(d) and 7(d) and (e)), together with an ample supply of sand to act as saltators (Type 6). We suggest that this sand supply and the combination of low relief and sparse vegetation (Figure 3(d)) contribute to making the delta the most prolific source of dust in this basin (54% of plumes originate from delta).

Some of the dust plumes originating from the gravel plain (Figure 3(e)) can be linked to the areas surrounding the playas and their channels with reasonable certainty. Other plumes clearly originate from the gravel plain but appear diffuse, and it is uncertain which surfaces are acting as the dust sources (this is the reason why the gravel plain could not be divided into smaller subunits in the analysis of the MODIS imagery in Figure 4). There are numerous playas spread on gravel plain and it is fairly certain that they play some role in the dust activity (Eckardt, et al., 2001). It is unknown whether this is as a direct source of predominantly saline dust or as an indirect driver of dust in producing very fine clastic material by extreme salt weathering from rock outcrops (Viles & Goudie, 2007), which is fluvially redistributed in runoff channels over time. The extensive areas of depositional crusts, the presence of Type 1 samples, the lack of vegetation and the low relief topography confirms the ephemeral channels draining the gravel plain as a likely source of dust (Figure 7(h)). The mechanism for emission most likely involves saltation as the channels also provide an ample supply of sand.

The stone pavements of the Kuiseb basin would seem an unlikely source given the gravel layer cover (Figure 7(f)). However, the dust potential of this surface needs further investigation. Wind tunnel experiments undertaken on stone pavements by Wang et al. (2012) in Western China and southern Mongolia, found that such surfaces have the potential to emit significant quantities of dust. The authors maintain that that the effect the gravel cover has on dust emission from these surfaces is complicated and that the gravel overlay may not be the most important control on the emissivity of the surface. With gravel covers of less than approximately 30%, sediment transport increased with increasing gravel cover. Beyond the 30% threshold dust emission decreased with increasing gravel cover. Xuan et al. (2004) agree that the gravel cover can both enhance and reduce the dust activity of

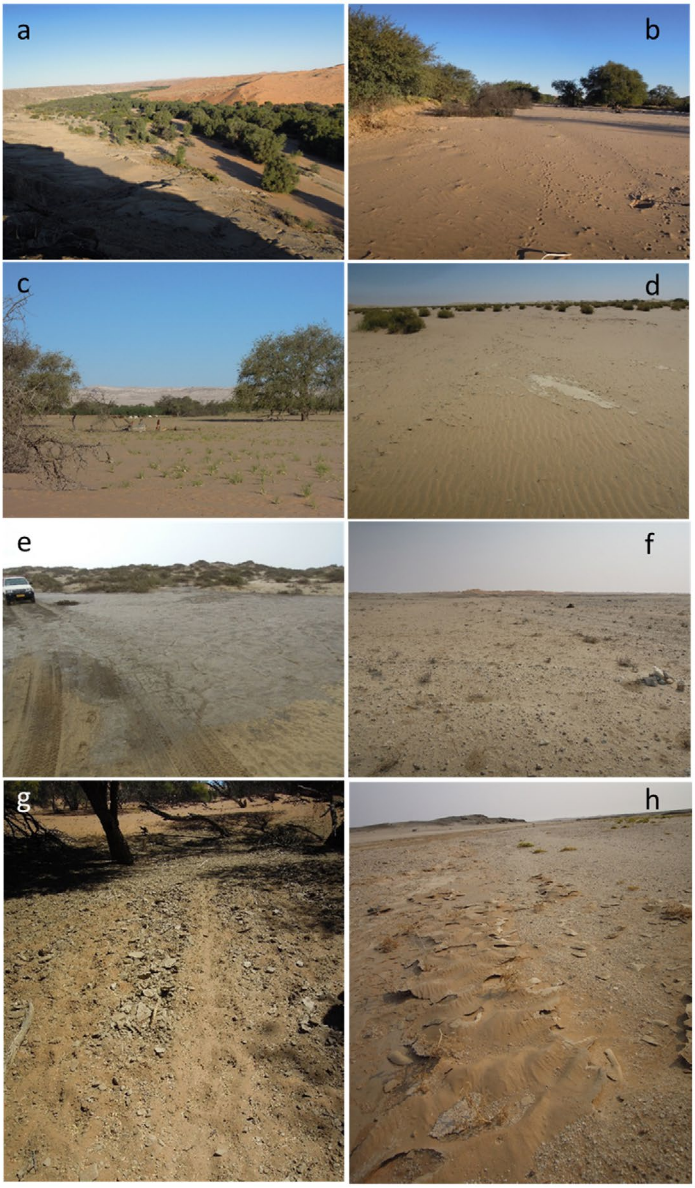

Figure 7. (a) The meandering nature of the river and incised valley between bedrock and the Sand Sea. This stretch falls within the RU: Upper river section in this study, (b) Towards the RM (middle river) section, the floodplain becomes wide, approximately 500 m and more. In this section A. Erioloba becomes the dominant woody species, (c) RL (lower river): The floodplain widens out even further and this is the most sparsely vegetated stretch of the river. The Swartbank and Rooibank A aquifer are situated within this segment and is the start of large scale water abstraction. This is also the most populated stretch of the river (see Figure 1), with abundant livestock farming around the settlements, (d) and (e) Extensive fine-grained sediment deposited as the flood water dissipate is found within the fan area of the delta (DFP) (f) The gravel plain stone pavements show considerable variability in terms of gravel density and mineralogy (GPS), (g) Livestock trampling is evident along the entire river included in this study, resulting in breaking up the depositional silt crusts and lowering the threshold friction velocity of the surface, (h) Ephemeral channels (wadis) dissecting the gravel plain also contain abundant supplies of fine-grained material suitable for entrainment by the wind.

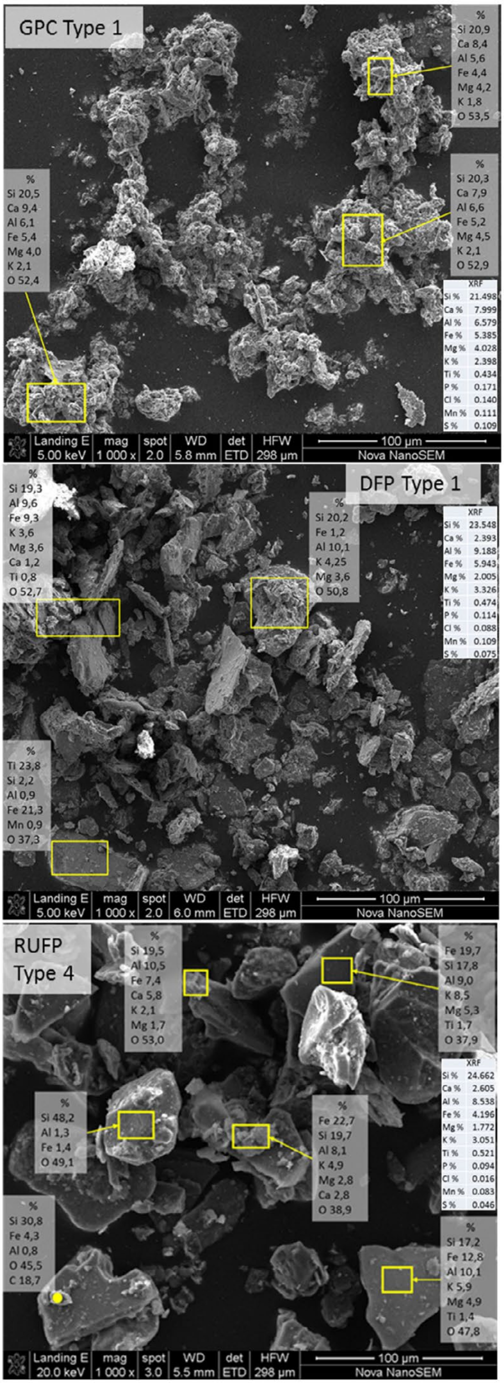

Figure 8. Scanning electron microscope (SEM) images of sediment from three different parts of the river catchment: GPC Type 1 (finest cluster) samples from the gravel plain channels showing aggregates of different minerals. DFP Type 1 is from the delta floodplain and confirms the fine-grained nature of this sediment. This sediment contains considerable mica with finer aggregates of different minerals. RUFP Type 4 sediment is from transect RU8, in the upstream section of the river with larger particle sizes and considerably less aggregations as is present in the two samples from the lower section of the river.

the surface. A complete cover of gravel can act to reduce dust emission, whereas reduced gravel armouring can affect the wind flow in various ways to enhance dust emission (Xuan et al., 2004). The Namib Desert stone pavements observed for this study consisted of various types and densities of gravel cover. It is therefore possible that the gravel pavement within the Namib Desert is a larger source of dust emission than previously thought, given the vast area covered by these stone pavements, their variable nature and the presence of a not insignificant (10%) proportion of silt-sized particles.

The SEM images confirm the results obtained for the particle size analysis and subsequent cluster types generated. The mineralogy and morphology of the dust will be different depending on the source area. Crust sediment from a gravel plain channel is made up of aggregates of different minerals, containing considerable calcite/aragonite (Figure 8). The ephemeral channel from which the sample was taken drains from a playa situated in an area with abundant calcrete duricrust into the main channel of the lower Kuiseb River. Also, present in the sample is very fine particulate organic matter (visible at 4204X magnification, 20 μm). This sample had the highest clay content (11%) of all the samples analysed. The delta and river floodplain sediments contained considerable mica (Figure 8 DFP Type 1, RUFP Type 4) derived from the widespread mica-schists found in the catchment (Ward, 1987). The effect of sediment sorting by floodwaters, with incorporation of material from the tributaries from the gravel plain is evident in the delta floodplain sample. The botryoidal material present in many of the samples appears to be soluble salts cementing other grains together (Pat Harris, Pers. Comm.). This results in fine dust particles adhering to other particles, which could be released during entrainment as particles undergo abrasion (Bullard, Mctainsh, & Pudmenzky, 2007). Dust activity from the different geomorphological units may have different impacts. Dust derived from the silt–clay deposits within the playas are rich in calcite (8% for GPC, see Figure 8), whereas dust from the river and delta contain less calcite (~2–3% for DFP and RUFP, see Figure 8) and more mica. The iron content of samples analysed varied from 4 to 6% and could influence marine biochemical processes (Jickells et al., 2005; Martin & Fitzwater, 1988). The particle size distributions of the individual samples analysed with SEM is included in the supplementary section.

Conclusion

The extended MODIS analysis for 2005–2014 confirms the delta as the most active dust source within the Kuiseb basin (accounting for 54% of plumes). The terminal stage of the river illustrates the dynamic fluvio-aeolian interactions identified to be important dust drivers, where aeolian transport takes over from low-energy fluvial transport (Koven & Fung, 2008). In contrast, the lower Kuiseb River main channel only accounted for 8% of all detected plumes, with the majority coming from the lower river section (RL: 5%) before fanning out into the delta. The ground based analysis of the surface sediments of the lower Kuiseb basin confirms the presence of a supply source of dust-sized sediment in the delta, along the entire length of the lower Kuiseb River. Due to a number of factors, most likely vegetation cover and topography, not all the fines are equally available for dust deflation. The relatively open and vegetation-free flood plains in the downstream section (RL) from Swartbank to Rooibank and delta (DFP) host the finest (Type 1) and most available material for entrainment along the river.

The gravel plain is a more significant source of dust than previously considered, based on the number of plumes detected with MODIS imagery (28%) and the presence of clay- and silt-sized sediment. Here, the ephemeral channels (GPC) interspersed with playas are the most likely source of dust based on the particle size analysis. The finest material within the catchment was found in these channels. Stone pavements cover extensive areas and are highly variable. Often the silt-substrate under the gravel armouring contains substantial amounts of dust-sized particles. Similar stone pavements in China and Mongolia have been shown to be significant sources of dust (Wang et al., 2012; Xuan & Sokolik, 2002) and this may be the case in the stone pavements of the Kuiseb catchment. The SEM analysis revealed that the morphology and mineralogy of the sediment from the gravel plain ephemeral channels and the main river appears to be substantially different. The fines located in the river consist predominantly of mica, whereas the gravel plain drainage network crusts are mainly made up of aggregates of different minerals.

The lower Kuiseb region is the biggest dust source along the entire west coast of Namibia, and potentially portraying an increase in activity from previously non-dust producing surfaces. Most sources are upwind of Walvis Bay, the second largest urban settlement in Namibia with an estimated population of over 80,000, which is projected to double by 2030 (Hitula, 2011). Furthermore, the diversification of the local economy beyond fishing and tourism is increasingly encroaching on the Namib–Naukluft National Park and includes exploration and mining, airport expansion and development along the lower Kuiseb along with water extraction and diversion. Such activities have the potential to promote dust production and dust exposure to an ever increasing portion of the inhabitants in the region. Future research efforts should examine the damage to gravel plain surfaces and establish their response to disruption, including the potential for dust production.

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