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Quantification of areal extent of soil erosion in dryland urban areas: an example from Windhoek, Namibia

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Soil erosion, while often studied in dryland settings for rural regions, has only occasionally been studied in urban settings. This study maps and quantifies areal extent and severity of water erosion in a dryland city (Windhoek, Namibia) using a snap-shot field survey approach. The results show that nearly 56% of the city could be affected by water erosion with signs of accelerated erosion in the form of rills and gullies. These occur mainly in the underdeveloped, informal and semi-formal areas of the city. Factors influencing the extent of erosion in Windhoek include vegetation cover and type, socio-urban factors, and to a lesser extent, slope. A comparison of an interpolated field survey erosion map with a conventional erosion assessment tool (the Universal Soil Loss Equation) highlights a mismatch in the spatial patterns found, underlining the inapplicability of traditional non-urban erosion tools to urban settings and emphasises the need to develop new erosion assessment and management methods for urban environments. Measures for controlling water erosion in the city need to be site-specific as the extent of erosion varied greatly across the city.

Keywords

Water erosion, Urban soil erosion, Quantifying erosion, Risk mapping

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1. INTRODUCTION

Accelerated soil erosion is one of the major global environmental problems that particularly affect regions within arid and semi-arid climate zones, where the ecosystems and soils are fragile (Tooth 2000; Vásquez-Méndez et al. 2011). Due to water limitations during the extended dry periods, vegetation is typically sparse, and thus cannot protect the soil surface when the high-intensity rain storms do occur, particularly at the onset of the wet seasons (Cornelis 2006; Ligonja and Shrestha 2015).

Soil erosion is normally studied and managed in rural regions, as it has adverse impacts on soil fertility and agricultural yields, and makes regional water management difficult. For example, through obstructions of stream channels, degradation of water quality, and reservoir sedimentation. Soil erosion is studied in urban settings less frequently, even though the adverse impacts can be as severe as for rural regions and include damage to buildings, gardens, car-parks, and roads. The main effects are the destabilization of eroded land and clogging of canals, and drainage systems due to the transportation of eroded soil materials (Sutherland and Tolosa 2000; Harris and Adams 2006). Networks of rills and gullies are the immediate signs of excessive soil erosion, mainly comprised of open incised and unstable channels. Here, we define gullies as channels that are more than 0.5m deep and rills are smaller (Gábris et al. 2003; Poesen et al. 2003). Rills and gullies occur where surface water flow has become confined, forming a small concentrated stream that begins to erode channels into the ground surface. The rill and gully networks destabilize urban infrastructure in their immediate surroundings, for example reducing access to and on properties, and potentially causing damage to underground utilities such as communication cables, pipes, and power cables. Rills and gullies are also an indicator of the spreading erosion, as once subsoil material has been exposed, the infiltration capacity of the soils is reduced, resulting in the generation of more overland flow and further soil erosion (Bryan 2000; Perroy et al. 2010).

A recent review by Shikangalah et al. (2016) on urban erosion studies shows that most urban studies focus on off-site erosion, for example, effects of sediment fluxes on urban channel networks (Nelson and Booth 2002; Poleto et al. 2009) or attached metal or organic contaminants (Jartun et al. 2008; Greestein et al. 2014), in contrast to the on-site effects of erosion, for example, soil loss and rill and gully formations in different urban areas (Ibitoye and Eludoyin 2010; Ehiorobo et al. 2012). These urban erosion studies are mostly located within temperate zones of the developed world, whereas only a few studies exist which have studied urban soil erosion for dryland settings, and very few of those studies were carried out in Africa (mostly in Nigeria, e.g. Jimoh 2001; Ehiorobo and Audu 2012; Omon and Oisasoje 2012).

Due to the different land-uses of built-up areas, standard methods of sampling such as erosion pins (Jimoh 2001), erosion plots or rainfall experiments (Rejman et al. 1998; Bryan 2000; Miyata et al. 2010) are not possible in the private courtyards, public paths, and spaces of settlements. To understand the pattern and impact of urban soil erosion, not only do standard parameters such as slope and vegetation cover and type (Pimentel and Kounang 1998) need to be quantified, but also other parameters describing the specific socio-spatial structure, and the visible damage of erosion to houses, roads, and other infrastructure within a settlement.

To our knowledge, no standard sampling protocol exists to meet this objective. Knowledge of the spatial extent of erosion is key to controlling soil erosion, and to reducing or preventing damage that occurs due to rills and gullies within more vulnerable residential areas of a city (Figure 1).

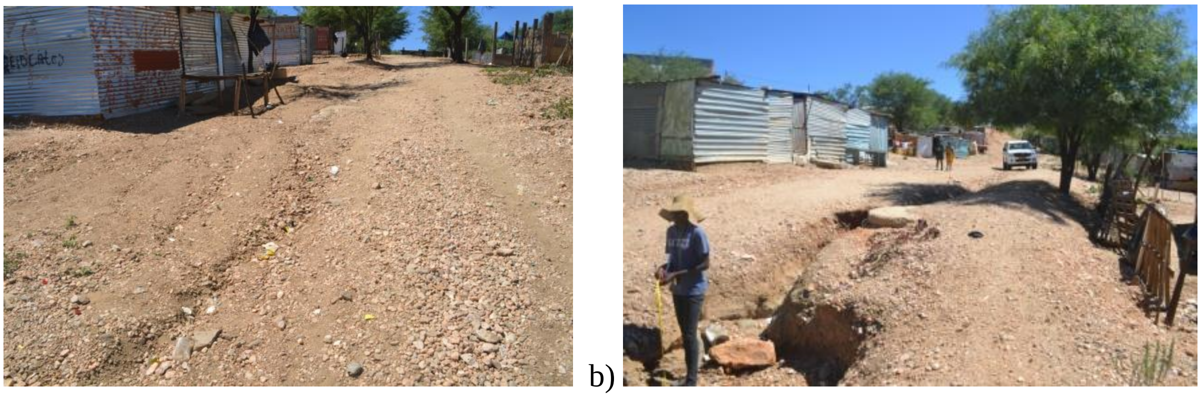

a) b)

Figure 1: Photos exemplifying: (a) rills and (b) gully erosion in Okahandja Park suburb.

This study aims to apply and test methods to quantify the extent and severity of soil erosion for different types of settlement within Windhoek, the capital of Namibia, which experiences an arid to semi-arid climate. The specific objectives are: (1) to assess the extent and severity of soil erosion in the form of rills and gullies, and the resulting damage to urban infrastructure in relation to vegetation cover and type, slope characteristics, and urban socio-spatial structure, (2) to interpolate the extent and severity of erosion to the spatial distribution of the Windhoek Metropolitan Area, and (3) to compare the erosion map derived from the field survey data with an erosion risk map derived using a traditional erosion quantification tool approach (Universal Soil Loss Equation) to assess the applicability of the latter approach for urban settings. The study is valuable for urban planning, land management and soil conservation in Windhoek, and for other similar urban areas in dryland regions.

2. MATERIALS AND METHODS

2.1 Location and characteristics of the study area

Namibia is one of the most arid countries in sub-Saharan Africa (Lahnsteiner and Lempert 2007; Greunen 2013), and is prone to recurrent droughts and flooding, and soil erosion during the rainy season. Windhoek is the capital city of Namibia. The city is located in central part of the country and is home to 15% of the country’s population 2, 104, 900 (National Planning Commission 2012; Pendleton et al. 2014), with a national growth rate of 0.67% per year (Namibia Demographics Profile 2014). Rapid urban growth and tremendous pressure from building developments combined with environmental vulnerability have resulted in environmental problems related to soil erosion (Mapani and Schreiber 2008; Greunen 2013). Hotspots of soil erosion such as visible rills have been observed across the city (Gray et al. 2008; Greunen 2013), affecting private and public housing, and infrastructure. Yet no estimates on the spatial extent of soil erosion are available.

Windhoek is about 22° 34′ 12″ S, 17° 5′ 1″ E and at ca. 1800 m elevation. The mean annual temperature ranges from 18 to 20°C while the mean annual rainfall ranges between 300 and 350 mm (Mendelsohn 2002). The city is characterized by longer drier periods than any other seasons: more months of summer than winter, and only three months of good rainfall, the least rain is received from June to July (Figure 2). As part of an arid country, the city is predicted to go under significant climate changes marked by increasing temperatures, drought and increased intensity in rainfall events (Lahnsteiner and Lempert 2007; Knapp et al. 2008).

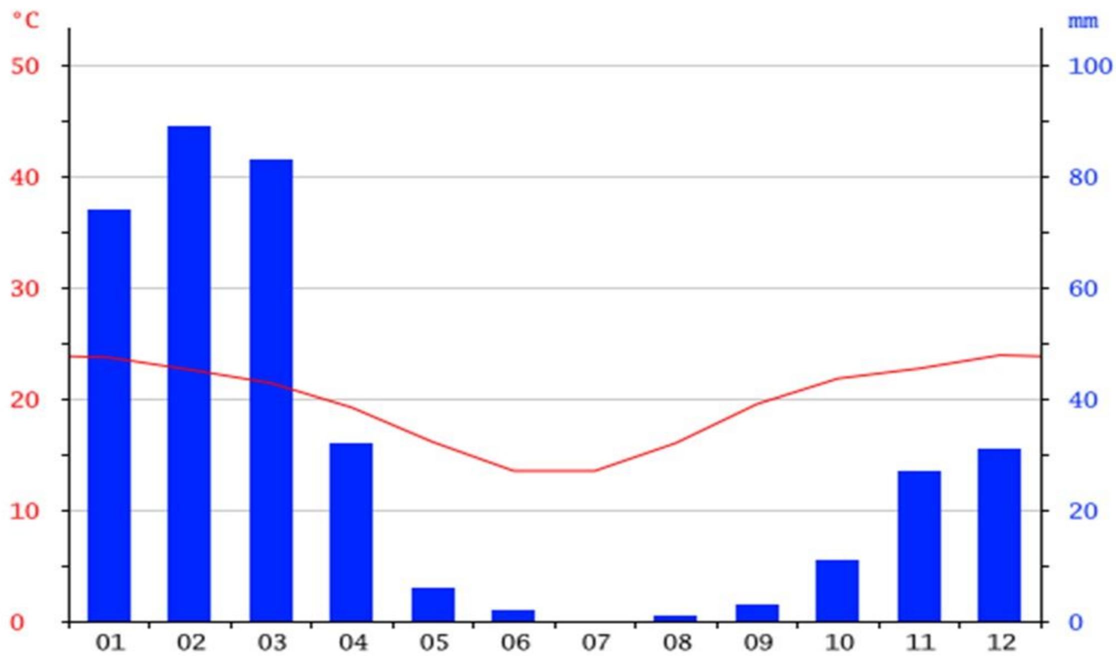


Figure 2: Mean monthly temperature (˚C) & precipitation (mm) of Windhoek (Climate-data.org 2012).

The city is surrounded by the Auas and Kuiseb Mountains formed from metamorphosed quartzite horizons and schist, respectively (Zhang et al. 2004; Mapani and Schreiber 2008; Tredoux et al. 2009). The weathered quartzite has soil deposits with good porosity and permeability (Murray et al. 2000), whereas biotite schist forms most Windhoek development land and the crystalline rocks are highly impermeable (Mapani and Schreiber 2008; Tredoux et al. 2009). As is typical for arid to semi-arid climates, vegetation cover is sparse in Windhoek. The city's natural vegetation is mainly dominated by shrubs and *Acacia* trees, such as *A. erubescens* and *A. hereroensis*, and short-lived grasses, such as *Stipagrostis* and *Enneapogon* species, with weedy herb species on the riverbeds (Gold et al. 2001, cf. Figure 3). Parks and gardens are very few and where available, they are dominated by turf grass.

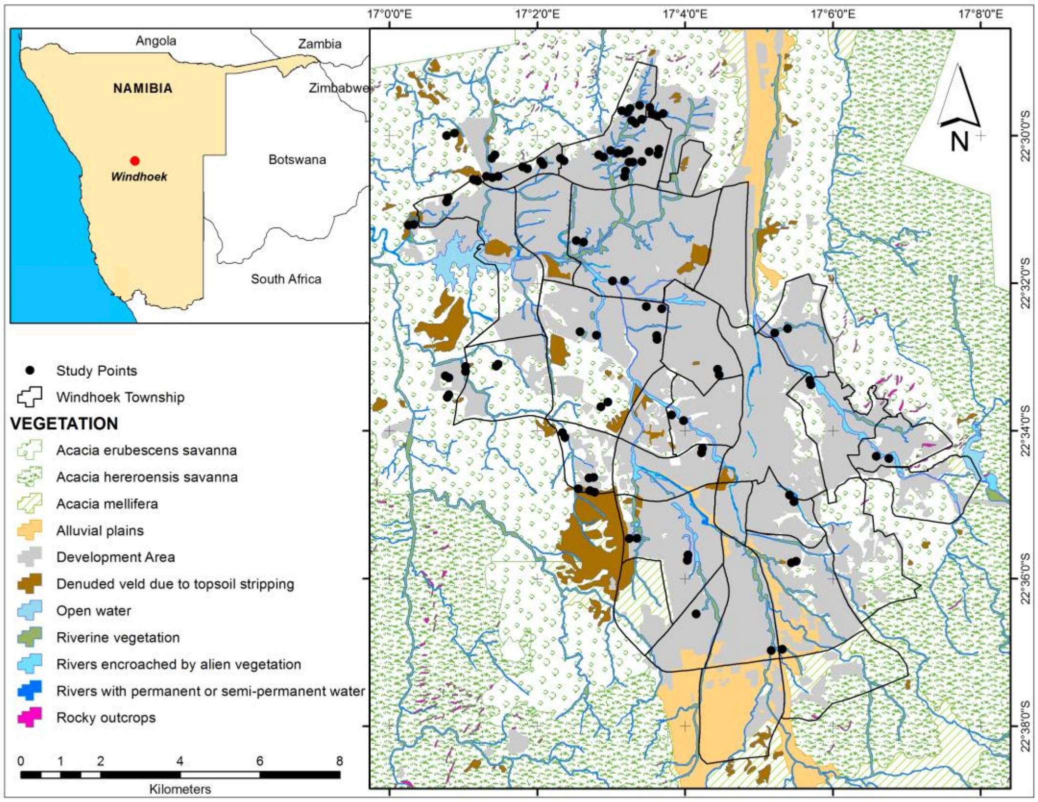


Figure 3: Location of the surveyed plots within the Windhoek Metropolitan Area of Namibia with its vegetation and land-use characteristics (City of Windhoek 2010).

2.2 Sampling design for the quantification of urban soil erosion

No standardized sampling protocol currently exists for the quantification of urban soil erosion. Soil erosion is normally quantified for rural regions where the size of agricultural fields or the riverine patterns of small meso-scale catchments are the dominant features for the set-up of the sampling design. As such a scheme is not applicable to the entirely different layout of an urban landscape, we developed a simple snap-shot sampling scheme which allowed us to sample across the Metropolitan area, and at the same time, allowed a plot-scale quantification of typical erosion features.

The sampling plot size, modelled on the size of a typical agricultural field plot, was set to 40 m x 80 m. The plot was large enough to contain typical urban features such as individual houses and courtyards, as well as vegetation patches, and erosional forms. The survey included mapping the distribution, length, and width of the erosional features for each plot. When smaller rills joined a main gully, the rill was measured from the starting point up to the convergence point and the main gully was measured separately. Although erosion features were mostly homogenous, there were a few cases when features had varying widths or depths along their length, and these were measured and an average was recorded (Herweg 1996). From the measurements, the total eroded area (m^2) of a plot was calculated by multiplying the length by the width of each rill and gully, and summing them together (Bewket and Sterk 2003). Table 1 summarizes the parameters which were sampled to enable an assessment on the extent and severity of soil erosion in relation to vegetation cover and type, slope characteristics, and socio-economic group. Specific emphasis was placed on the detailed survey of erosion gullies and rills, as they are the typical signs of excessive soil erosion by water.

Table 1: Parameters of the snap-shot field sampling for the quantification of urban soil erosion in 40 m x 80 m plots for the Metropolitan Area of Windhoek

Erosion parameters	**Explanation**
1. Gully (m) length, width & depth 2. Rill (m) length, width & depth	Features used to estimate the extent of erosion (m^2) in sampled plots
Soil and terrain parameters	**Explanation**
1. Surface soil type 2. Slopes categories	Dominant topsoil group: stone, gravel, sand or clay Flat= 0°, gentle= 1-20°, medium= 20-45°, steep= >45°
Surface cover	**Explanation**
1. Vegetation (%): Trees, Grass	Area of trees cover with grass were calculated
Damages	**Explanation**
1. Damage (%)	Visual estimate of structural damage (e.g. to houses or streets) in each sampled plot
Socio-spatial structure	**Explanation**
1. Type of settlement 2. Income class	Categories: formal, semi-formal and informal Average income classes: very low, low, middle, high and very high

During February and March of 2015, a total of 95 plots distributed across the city were surveyed. The plots were selected randomly with one or two replicates in each neighborhood, from pre-defined regions that include typical assemblies of buildings, bare areas, footpaths, and roads. However, in the north-west of the city, which are dominated by semi-formal and informal settlements. There are more open areas than in the southern part, which are dominated by formal settlements comprised of wealthier people. Consequently, there are more plots being assessed in the northern part of the city. Socio-spatial information on the type of settlement and income class of the settlement were recorded qualitatively. The number of plots surveyed is 16 in formal areas, 28 in semi-formal areas and 51 in informal areas. For income classes, we surveyed 16 plots in very low class, 20 in low class, 18 in middle class, 19 in high class and 22 very high-income class.

In the absence of official maps that could be used for the classification of the different income classes and settlement types, areas were classified based on the knowledge of the municipal officers via personal communication with authors, as well as observations during fieldwork. The income classes were based on the general average income classification while the settlement types were based on land tenure. Semi-formal settlements are areas with legal land tenure but attract many low-income people (Soliman 1996) who construct shacks or corrugated iron houses on the land. The informal settlements are areas where groups of housing units have been constructed on land that the occupants have no legal claim to or are not in compliance with current planning and building regulations (Wakhungu et al. 2010; UN-Habitat 2015). While the semi-formal settlements are mostly inhabited by people from the low-income class, some areas also belong to the middle-income class. The formal settlements are inhabited partly by people of the low- and middle-income class, as well as all of the high- and very high-income classes.

2.3 Spatial analysis of urban erosion extent and patterns

The spatial extent of excessive erosion in the form of rills or gullies was estimated as a percentage of the area of each 40 m x 80 m plot. Although these percentages might appear to be relatively small, the presence of rills and gullies is already a sign of excessive erosion, suggesting large erosion rates in the direct vicinity. Moreover, a real extent of the erosion is still sizeable as it renders the affected land useless for urban infrastructure such as buildings or parking. A standard extrapolation toolbox in the ArcGIS software (ESRI, version 9) was employed to interpolate the percentage area affected by excessive erosion to the entire study area within the Municipality of Windhoek using the Inverse Distance Weighting (IDW), Spline and Natural Neighbor methods (Bartier and Keller 1996; Kurtzman and Kadmon 1999; Kravchenko 2003; Karydas et al. 2009; Guo et al. 2010; Chen and Liu 2012). This approach has been used in England and Wales (Skinner and Chambers, 1996; Evans, 2002; Mchugh et al. 2002).

Soil risk was calculated with the traditional Universal Soil Loss Equation (USLE) after Wischmeier and Smith (1978). In USLE, erosion is a multiple of rainfall erosivity (the R factor, which equals the potential rainfall energy); this multiplies together the resistance of the environment, which comprises K (soil erodibility), LS (the topographical or slope and length factor), C (plant cover or land-use and farming techniques) and P (erosion control practices) (see for example Ma et al. 2003; Bilaşco et al. 2009; Schönbrodt et al. 2010; Tamim et al. 2012). Since it is a multiplier, if one factor tends towards zero, erosion will tend towards zero.

The USLE is normally employed for rural areas, but parameterization data are available for settlements and urban settings. The LS was derived from a Digital Elevation Model (DEM) of Windhoek with a spatial resolution of 5 m. The calculation procedure of the LS factor followed that of Hui et al. (2010), Arekhi et al. (2012) and Farhan et al. (2013) and employed the Arc Hydro extension of ArcGIS (ESRI, Version 9). To calculate the R factor, mean annual precipitation based on 20 years (1995–2015) of data from four stations (only one formal station) was used. As no coherent measure for soil conservation exists (ignoring the rare prevention lines of sand-bags and tires on private properties), the P factor for erosion control practices was set to 1 (e.g. Kuok et al. 2013, Catani et al. 2014). In the absence of a soil map, the K factor was modelled from the underlying geological material map layers (Table 2) while the C factor (Table 3) for land-use was derived from normalized difference vegetation index (NDVI) map layers, both data for map layers are provided by the municipality, City of Windhoek (2010).

Table 2: K factor (soil erodibility) values.

Geology Type	K Factor Values	Total Cover (%)
Alluvium	0.16	4.27
Amphibole schist	0.28	0.11
Amphibolite	0.43	0.87
Biotite schist	0.66	77.34
Quartzite	0.81	4.27
Sand calcrete gravel	1.0	13.14

Table 3: C factor (plant cover) values.

Land cover	C factor values	Total cover (%)
Acacia erubescens savanna	0.11	16.23
Acacia hereroensis savanna	0.15	3.03
Acacia mellifera dominated lowlands	0.23	3.47
Alluvial plains	0.31	5.08
Degraded lands	0.47	9.09
Denuded veld due to topsoil stripping	0.50	2.29
Development area	0.66	54.70
Open water	0.69	0.29
Riverine vegetation	0.78	3.76
Rivers encroached by alien vegetation	0.98	1.63
Rivers with permanent or semi-permanent water	0.00	0.39
Rocky outcrops	1.00	0.04

3. RESULTS

Only the percentage of erosion (rather than areal value for the 3200 m^2 plots) will be discussed as they are thought to be more meaningful when the actual erosion is scaled up to the extent of the entire city. As vegetation and slope are relevant parameters affecting soil erosion, erosion occurrence is assessed as a function of slope category, and vegetation cover in relative terms and shown as a percentage (%) of plot area comprising erosion features. Generally, greater vegetation cover and low slope result in decreased erosion, whereas decreased vegetation cover and steep slope result in accelerated erosion.

3.1 Analysis of the effects of slope, vegetation and socio-spatial structure on urban erosion

The snap-shot sampling on urban soil erosion for the Metropolitan Area of Windhoek shows that there is extensive soil erosion by water including in the most severe form (rills and gullies) across the entire city. Rills and gullies are normally associated with accelerated erosion and occur in around 45% of the sampled plots (accelerated erosion was assumed if rill and gully erosion covers an area larger than 10 m^2 per plot, giving clear and well-pronounced erosional features); damage to streets and houses occurs in around 13% of the plots. Table 4 shows that the area affected by erosion reaches a maximal value of 283 m2 (8.8% of the plot). The average affected areas are 25 m^2 and the large 215 standard deviation is 43 m^2. Although N* in Table 4 indicates the number of plots in which the parameters occurred, the mean was calculated for all plots assessed (95 plots), hence 95 was the denominator for the average.

Table 4: Summary statistics of the urban soil erosion field survey of 95 sampled plots

Attribute	N*	Minimum	Maximum	Mean	Std. Deviation
Tree cover (%)	88	1.0	21.0	6.49	4.30
Shrub cover (%)	94	1.0	10.0	3.62	1.70
Grass cover (%)	95	1.0	80.0	20.31	21.14
Total vegetation cover (%)	95	3.0	90.0	29.86	23.54
Gullies total length (m)	10	3.0	40.0	18.70	11.38
Gullies total width (m)	10	0.4	4.0	1.94	1.31
Gullies total area (m^2)	10	1.5	160.0	42.53	46.25
Gullies total area (%)	10	0.4	37.6	10.00	10.87
Rills total length (m)	60	2.0	85.0	24.52	18.23
Rills total width (m)	60	0.2	4.1	0.98	0.71
Rills total area (m^2)	60	0.4	282.9	32.47	46.84
Rills total area (%)	60	0.02	14.5	1.67	2.40
Total eroded area (m^2)	63	0.4	282.9	37.68	48.83
Total eroded area (%)	63	0.2	11.9	1.59	2.06
Total bare surface eroded (%)	63	0.03	31.3	2.91	4.80

Figure 4 shows erosion occurrence as a function of settlement and income class. Many of plots within informal and semi-formal areas are affected by accelerated erosion (75% and 68%, respectively), whereas only 24% of plots within formal settlements show signs of accelerated erosion. Street and house damage occurred mainly in informal areas (in 44% and 50% of the plots, respectively, Figure 4). The occurrence of accelerated erosion as a function of income gives a similar but more detailed picture. Plots within areas of very low to low income are affected more than average, whereas plots within areas of high to very high income show little erosion. Accelerated erosion also occurred frequently in plots in middle income areas: these are partly within both the formal and semi-formal settlement areas.

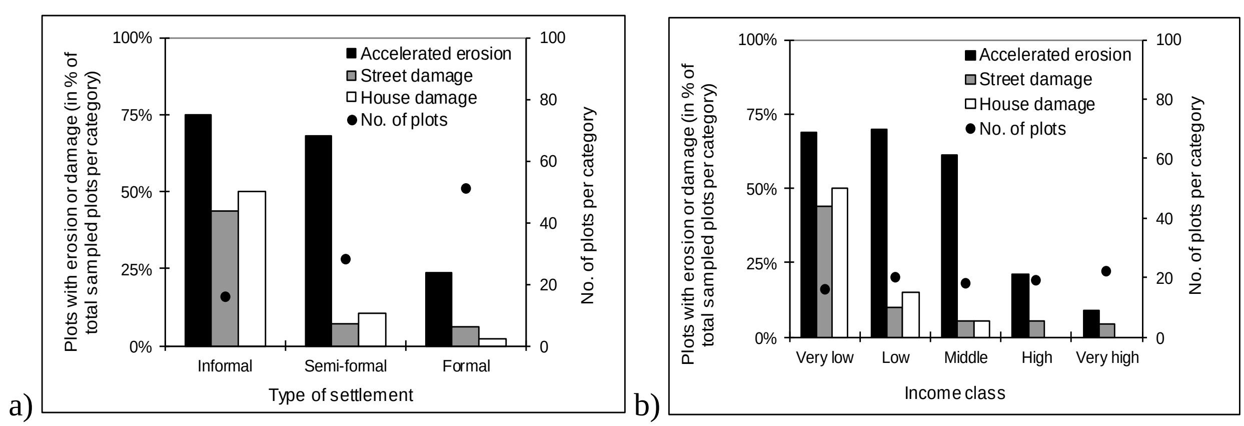


Figure 4: Plots showing accelerated erosion and damage to streets and houses as a function of: a) settlement type, and b) income class.

Figure 5 illustrates the relationship between vegetation cover and socio-spatial factors. Vegetation cover is highest in the formal settlements and those areas with high to very high income, and vice versa for informal settlements and those with very low to low incomes (Figure 5). The lower levels of accelerated erosion in the formal settlements are thus associated with high vegetation cover, whilst the informal and semi-formal settlements have lower vegetation cover and considerable accelerated erosion.

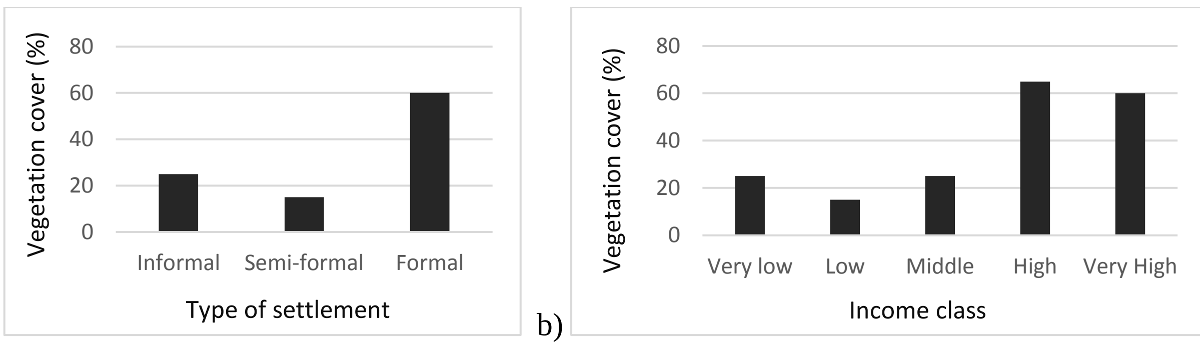
a)
b)


Figure 5: Vegetation cover of surveyed plots as a function of: a) type of settlement, and b) income class.

Figure 6 shows the distribution of plots affected by erosion (% area of each 3200 m^2 plot) as a function of vegetation cover and slope. The incidence of accelerated erosion decreases with an increase in vegetation cover (Figure 6a), although street and house damage increases with vegetation cover. Furthermore, erosional damage was slightly higher on medium slopes (20-45˚) than gentle slopes (1-20˚) with very little damage on flat (0˚) and steep (>45˚) slopes, but there are only three plots surveyed in each of these categories (Figure 6b). The flat slope category in Figure 6b shows 100% house damage because all 3 of the surveyed plots were affected.

a)
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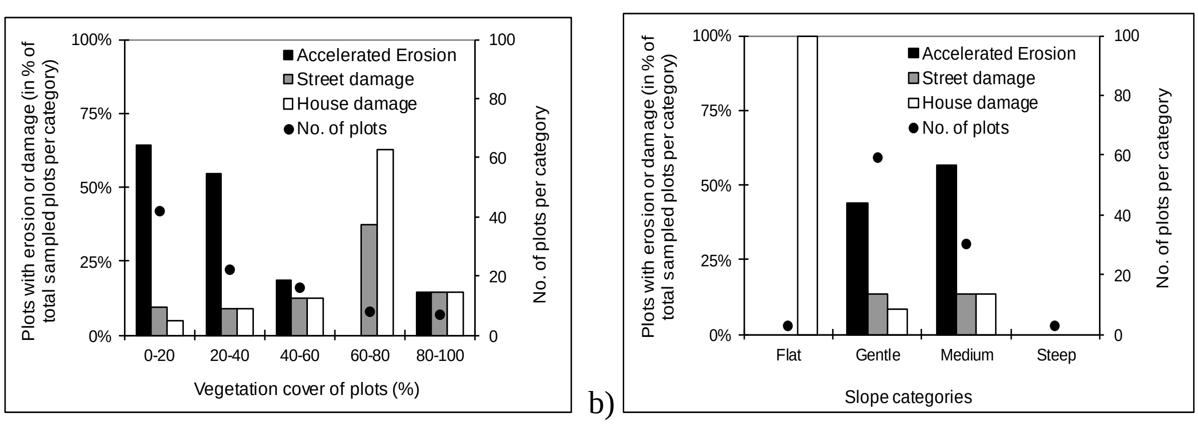


Figure 6: Plots with accelerated erosion and damage to streets and houses as a function of: a) vegetation cover, and b) slope.

The vegetation cover of the plots is generally low with an average cover of around 30%, mostly composed of grass (on average 20%) with a considerably smaller average cover of trees and shrubs (Table 4). Around 64% of plots with vegetation cover up to 20% are affected by accelerated erosion, but only 14% of plots with a high vegetation cover of 80–100% (Figure 6a). Plots with less than 20% grass cover show widespread erosion, while plots with more than 50%

grass cover show no erosion (Figure 7b). Erosion also declines with increasing tree cover, with no or very little erosion for plots with more than 10% tree cover (Figure 7c). Trees, however, only occur with an average cover of 6% (Table 4), and thus they are not a dominant factor in our plots. The effect of slope on erosion is greater in plots with medium slopes than gentle ones. Very little erosion is detected on flat and steep slopes, likewise, only three plots were surveyed in each, limiting their usefulness on the study. (Figure 7d).

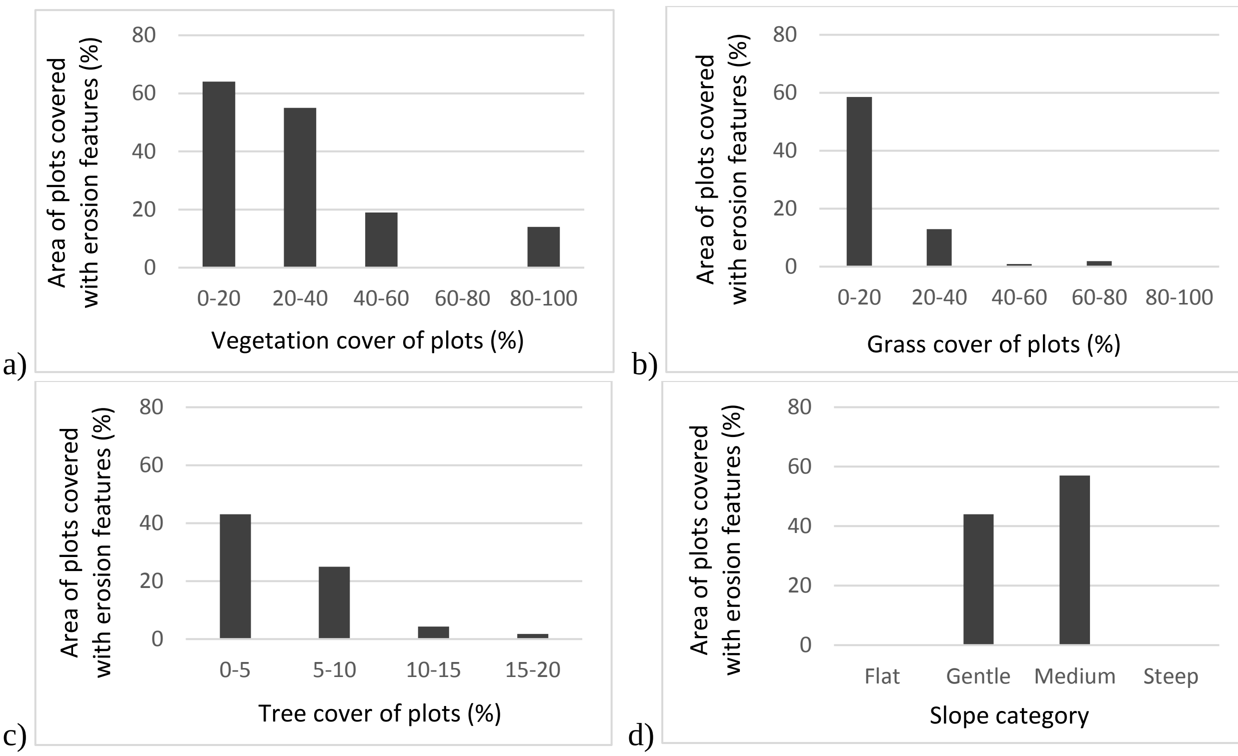


Figure 7: Plot areas affected by accelerated erosion (rills and gullies) as a function of: a) total vegetation cover, b) grass cover, c) tree cover, and d) slope

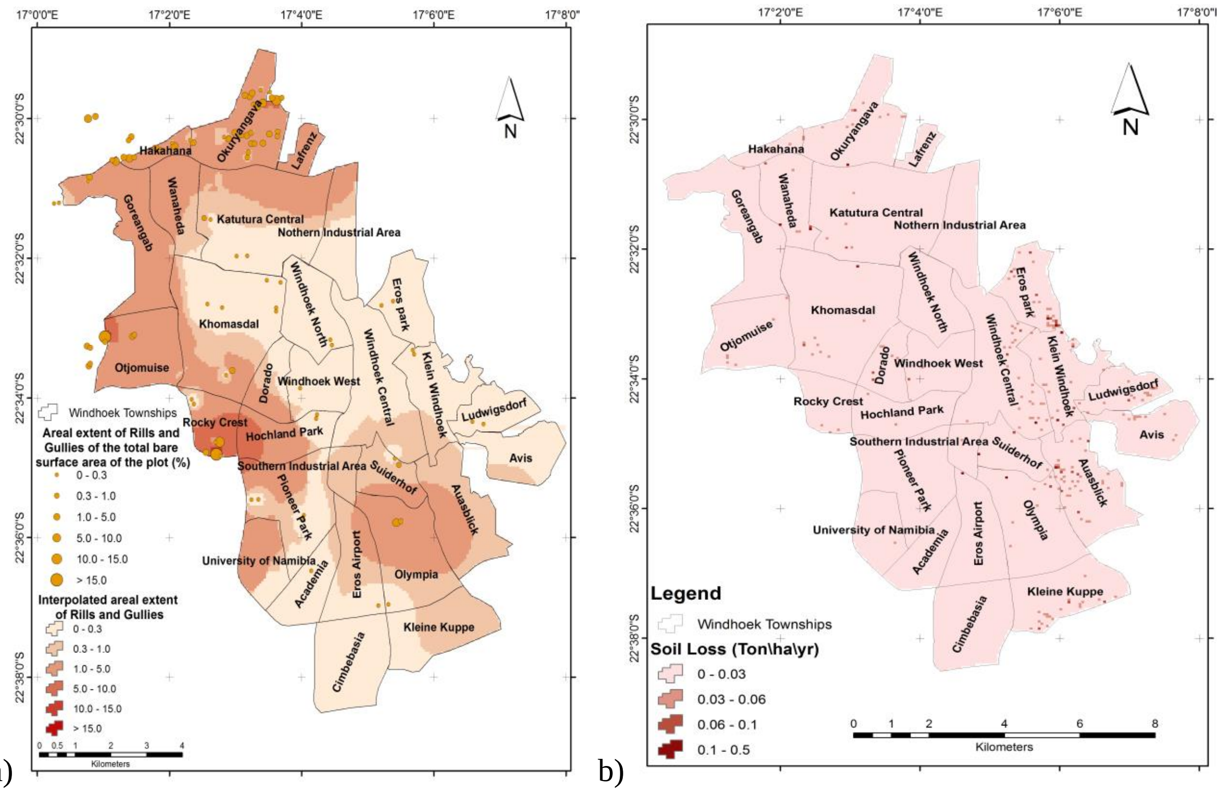
3.2 Spatial analysis of urban soil water erosion in Windhoek

By interpolating our plot results to the whole city, around 56% of the city could be affected by accelerated soil erosion, with more than 0.3% of the surface showing significant signs of accelerated erosion in the form of gullies or rills (Table 5).

Table 5: Percentage area of Windhoek for six levels of soil erosion defined by the mean area of bare surface covered by rills and gullies derived from the field survey data

Level of soil erosion	Ranges of eroded area (%)	Estimated affected city area (%)
Minimal	0 - 0.3%	43.4
Low	0.3 - 1%	20.8
Moderate	1 - 5%	33.6
High	5 - 10%	2.1
Very high	10 - 15%	0.05
Extremely high	>15%	0.03

Soil erosion is most severe in the northern and western borders of the city, especially in the Rocky Crest township of the city (Figure 8a). The interpolation map shows low to very low erosion for the central, eastern, and southern areas. The spatial distribution of erosion occurrence mirrors the spatial vegetation cover: plots with limited vegetation cover are located mainly in the north-western part of the city, while those with higher vegetation cover are in the central to eastern part of the city. The spatial distribution obtained from the USLE model gives a divergent pattern of soil erosion occurrence in comparison to the field results (Figure 8b).



a) b)

Figure 8: Spatial pattern of erosion levels from: a) interpolation of the field snap-shot sampling, and b) USLE annual soil loss in Windhoek

The USLE model predicts that 3.14% of Windhoek experiences an annual soil loss ranging between 0.06 and 0.5 ton ha^{-1} yr^{-1} mainly in the eastern part of the city, whereas 5.25% of the city experiences soil loss ranging between 0.03 and 0.06 ton ha^{-1} yr^{-1}. The rest of Windhoek city (91.6%) is predicted to experience extremely low soil loss of less than 0.03 ton ha^{-1} yr^{-1} (Table 6).

Table 6: Soil loss in Windhoek derived from the USLE approach

Level of soil loss	Range of soil loss (ton ha^{-1} $year^{-1}$)	Corresponding city area (%)
Minimal	0 - 0.007	66.98
Low	0.007 - 0.03	24.63
Moderate	0.03 - 0.06	5.25
High	0.06 - 0.1	1.94
Very high	0.1 - 0.5	1.20

4. DISCUSSION

4.1 Factors influencing water erosion and the implication for management in Windhoek

The field campaign showed that erosion in its accelerated form such as rills and gullies is widespread throughout the city of Windhoek. Although the percentage of areas affected by accelerated erosion in the sampled plots appears to be small, it should be kept in mind that the occurrence of rills and gullies is already a warning signal of excessive erosion whose appearance indicates the occurrence of extended erosion of adjacent slopes during heavy rainstorm events.

The extent and severity of soil erosion is associated with lower income classes and sparse vegetation cover, and are spread over the three settlement types. Apart from the low vegetation cover, the high frequency of erosional damage in the very low, low, and middle-income areas can be directly linked to inadequate drainage systems and poor land management. In these areas, vegetation cover is likely to have been reduced by the intentional clearance of vegetation (Harper and Maritz 1998; Gold et al. 2001), either to use the wood or simply to make the gardens look tidier (Gold et al. 2001). We suppose that residents are not aware that such clearance has adverse effects on the state of their land. In contrast, the high to very high-income areas have the least occurrence of erosion and the most vegetation cover. This finding suggests that potential future management plans should not only consider the settlement type, but other socio-spatial factors such as the income class for the organization of potential prevention schemes. Proper planning and sound land management strategies are vital for minimizing urban erosion, especially when water erosion is ranked one of the most significant forms of land degradation (Valentin et al. 2005; Tamim et al. 2012; Kairis et al. 2013), particularly in semi-arid areas (Ayoub 1998; Cantón et al. 2011).

4.2 A comparison of the field survey erosion map to the USLE soil loss risk map

An interpolated field survey erosion map and the results of soil loss estimates using the USLE model both show distinctive spatial patterns of erosion, but there are differences in the predicted occurrence and severity of erosion across the Windhoek city area. This casts doubt on the applicability of the USLE model in urban settings.

The USLE model predicts very low rates of soil erosion for almost the entire city (up to 0.5 tons ha^{-1} yr^{-1}). According to Wall et al. (2002), soil erosion can be considered moderate at values of up to 22 tons ha^{-1} yr^{-1}. The USLE approach predicts increased soil erosion in parts of the central and eastern regions of the study area where no or very little soil erosion was found during the field survey. Instead the field study found signs of excessive soil erosion in the western and north-western areas. Both the USLE model and the interpolated field survey map predict erosion in the south-eastern part of Windhoek. The USLE approach mainly reproduces the spatial structure of slope, as this is a dominant factor in the USLE model equation. The city lies in a valley, but the landscape of the area is largely made of several hills, and the USLE equation reflected on the hill slopes for potential soil loss. The comparison therefore shows that a standard USLE approach is not appropriate in an urban setting such as Windhoek, mainly for two reasons: 1) urban types of vegetation cover such as gardens and urban green areas surrounding footpaths and streets are not implemented in the USLE approach and 2) the management of urban green areas (e.g. intentional clearance or erosion control measures such as sand-bags) is not considered, although the management significantly affects the occurrence of urban soil erosion in the study area.

5. CONCLUSIONS

With nearly 56% of Windhoek predicted to be affected by water erosion, the study demonstrates that soil erosion is a significant problem in urban areas and likely to be in similar urban areas in dryland zones. While income class is not a common attribute for the quantification of soil erosion outside cities, it is clearly associated with the severity and pattern of soil erosion in the Windhoek metropolitan area. Additionally, grass cover of more than 40% is associated with much less erosion, whereas the presence of trees and shrubs is too limited to particularly influence the occurrence of erosion.

Our results strongly suggest the need for site-specific erosion control measures in the various townships (income classes) of Windhoek. The produced soil erosion map indicates most severe erosion signs in the north-west (where many lower income areas are located) compared to the central, southern and eastern parts (location of higher income classes). The contrasting results of the widely-used erosion modelling tool (USLE) strongly suggest that this model is less suitable for urban settings, especially as it ignores the small-scale differences in vegetation cover which are linked to the different land-management practices. This emphasizes the need to develop new erosion assessment and management methods specifically for urban environments. Both approaches, however, can still be useful, but for different purposes. The USLE estimations can be used to highlight areas of potential erosion vulnerability which are related to slopes and provide rapid results prior to the development or land occupation of suburban areas, while field survey approach is indispensable for providing detailed information of water erosion under field conditions at finer scales and after land occupation.

The mapping of the extent of erosion in Windhoek was the first of its kind, as no sampling protocol existed before that could guide soil erosion mapping over an entire city area in a dryland setting. The resulting map is likely to become a valuable tool for guiding land-use and soil-management plans, as it clearly distinguishes high- and low-risk erosion zones. It appears there is no awareness of the severity of soil erosion by city managers who refused to even acknowledge that soil erosion by water occurs in Windhoek. We therefore call for studies that try to understand the perceptions of the local population and authorities towards the relevance of soil erosion in terms of land and city management.

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