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LANDSCAPE EVOLUTION AND CLIMATE IN MADAGASCAR: LAVAKIZATION IN THE LIGHT OF ARCHIVE PRECIPITATION DATA

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ABSTRACT. *In Madagascar, soil erosion is significant even when it is compared to world averages. A resulting special geomorphic feature is a form of gully erosion known as lavaka that appears in the highlands of the country. Lavakization (the generation and development of these features) is due to rather unique multifactorial environmental conditions. Among many factors (geology, soil composition, human activities, etc.), the spatial and temporal distribution of precipitation is a key factor influencing the behaviour of lithology and the vegetation cover of the island. The inter-annual variability in precipitation seems to be responsible for the enhanced generation of small cracks that might eventually lead to the development of a gully. However, the way of the development of such gullies is unknown. To what extent the actual precipitation pattern contributes to the aforementioned phenomenon has not yet been studied in great detail.*

This paper aims to analyze lavaka distribution with GIS methods and to study the relation between lavaka density and climatic conditions. Study areas have been designated throughout the country and lavakas have been identified using satellite imagery. Archive climate data of the study areas have been used to understand the influence of the weather on gully density. Data show that the spatial distribution of precipitation is connected to the appearance of lavakas to a given extent and its effect is further strengthened by the tropical cyclones. However, neither the amount of the precipitation, nor its variability alone can explain the high variation found in the spatial distribution of lavakas. Further multidisciplinary studies are necessary to draw conclusions about lavaka formation and to describe the process of lavaka development.

Evolución del paisaje y clima en Madagascar: lavakización en relación con los datos de precipitación

RESUMEN. *En Madagascar, la erosión del suelo es muy elevada, incluso cuando se compara con los promedios del resto del mundo, dando lugar a formas de* *relieve especiales, conocidas como lavakas, que aparecen en las regiones montañosas de Madagascar. La "lavakización" (generación y evolución de estas formas) se debe a una multitud de condiciones ambientales únicas. De entre las muchas condiciones, (geología, composición del suelo, influencia antrópica, etc.), la distribución espacial y temporal de la precipitación es el factor más importante para explicar el comportamiento erosivo de la litología y las características de la cubierta vegetal de la isla. La ocurrencia de estaciones secas y lluviosas es aparentemente responsable del crecimiento de pequeñas grietas que eventualmente pueden conducir al desarrollo de lavakas. Sin embargo, se desconoce cómo se desarrollan esos barrancos. Además, la pregunta de hasta qué punto la precipitación y su pauta afecta al fenómeno mencionado todavía no ha sido contestada.*

El objetivo de este artículo es analizar la distribución de lavakas con métodos de GIS y examinar la relación entre su densidad y las condiciones climáticas. Las áreas de estudio han sido elegidas a lo largo del país, y las lavakas han sido identificadas con la ayuda de imágenes de satélite. Se han utilizado datos climáticos para comprender la influencia del clima en la densidad de los barrancos. Los datos de la precipitación nos permiten establecer una correlación entre la aparición de los barrancos y la distriubución espacial de la precipitación. Además, su efecto es incentivado adicionalmente por ciclones tropicales. No obstante, ni la cantidad o la variabilidad de la precipitación por sí solas pueden explicar la variedad existente en la distribución espacial y el tamaño de las lavakas. Nuevas investigaciones multidisciplinares son necesarias para conocer mejor los procesos de desarrollo y la aparición de lavakas.

Key words: Madagascar, lavaka, gully, soil erosion, land degradation, climate.

Palabras clave: Madagascar, lavaka, erosión del suelo, degradación del suelo, clima.

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1. Introduction

Madagascar, the fourth biggest island of the world, is unique in many respects. Among others, its wildlife diversity and numerous endemic species are well known. Nevertheless, it is quite special in terms of erosional processes. The island, with an area of 587 000 km^2, is characterised by a special combination of erodible soils and varying temporal and spatial distribution of precipitation. The significant soil erosion in the island (Cox *et al*., 2010) is attributed to a landform type found throughout the island known as lavaka (Riquier, 1955; Cox *et al.,* 2010). The study of this landform and its development has special importance, since it causes several problems for the local inhabitants (Bakoariniaina *et al*., 2006). Soil degradation and the resulting sediment yield reduce the productivity of the croplands and may damage infrastructures (Mulder and Idoe, 2004; Randriamanga *et al*., 2006). Beside the study of this unique landform, Madagascar is an important place to study erosion processes (Cox *et al*., 2010), because of the long-term erosion rates due to lavakas might be significant as well.

Lavaka is a Malagasy word meaning 'hole' but in the scientific literature its use is restricted to a well-known phenomenon of a special gully type that is found only in Madagascar (Riquier, 1955; Andriamampianina, 2006; Cox *et al*., 2009; Zavada *et al*., 2009; Cox *et al*., 2010). Although there are similar erosion forms named differently, e.g. in the USA or Brazil (Andriamampianina, 2006; Unruh *et al*., 2010), their shapes, spatial pattern and evolution seems to differ considerably from that of lavakas (Cox *et al*., 2010).

A typical lavaka is generally amphitheatre-shaped with vertical walls and flat base that ends downstream in a narrow outlet (Fig. 1). Some of them have pillars of regolith on their bottoms (Wells and Andriamihaja, 1993). Lavakization (the formation and development of this type of gullies) starts abruptly with small cracks in the soil that develop rapidly to larger gullies with steep walls, and a relatively flat bottom. Erosional crests or pillars may remain in the internal part. After an initially rapid evolution phase the growth rate decreases gradually till the lavaka reaches an inactive vegetated phase (Cox *et al*., 2004). Despite its negative role in soil erosion, lavakas are often used for agronomical purposes (Andriamampianina, 2006; Zavada *et al*. 2009; Unruh *et al*., 2010) because of their favourable microclimate and soil properties.

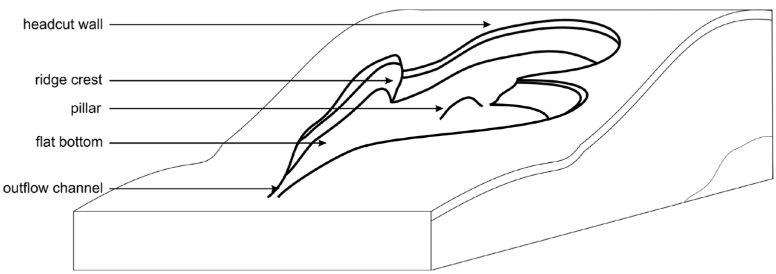

Figure 1. Illustration of a typical lavaka.

Lavakas are specific mainly in the highlands of Madagascar. Despite of the several decade long researches, the evolution and the reasons for the formation of these geomorphic features are unknown. In the last half-century scientists have proposed numerous models. Riquier (1954) mentioned that one of the main reasons to this kind of erosion is the anthropogenic impact. According to this opinion, grazing of domestic animals and burning of vegetation for new cultivable lands cause severe erosion processes to occur. However, it has been noted that there are several lavakas in uninhabited areas as well (Mietton *et al*., 2014). Distinct research groups agree upon that lavaka formation requires a specific combination of lithology, weathering profile, topography and seasonal climate (Wells and Andriamihaja, 1993; Cox *et al*., 2004, 2010; Randriamanga *et al*., 2006; Zavada *et al*., 2009). Cox *et al*. (2004) and Zavada *et al*. (2009) interpreted lavaka as a primary response of the unstable landscape to recent tectonic activity.

Cox *et al*. (2010) outlined a specific area (Fig. 2) characterised by high lavaka density. This area is termed as the lavaka-prone area (hereafter referred to as LPA) and is characterised by highly weathered soils with a top layer that is more resistant to erosion (Cox *et al*., 2010). Lavakas are mostly formed in convex slopes covered by thin vegetation (grassland) and shrub patches (Wells and Andriamihaja, 1993).

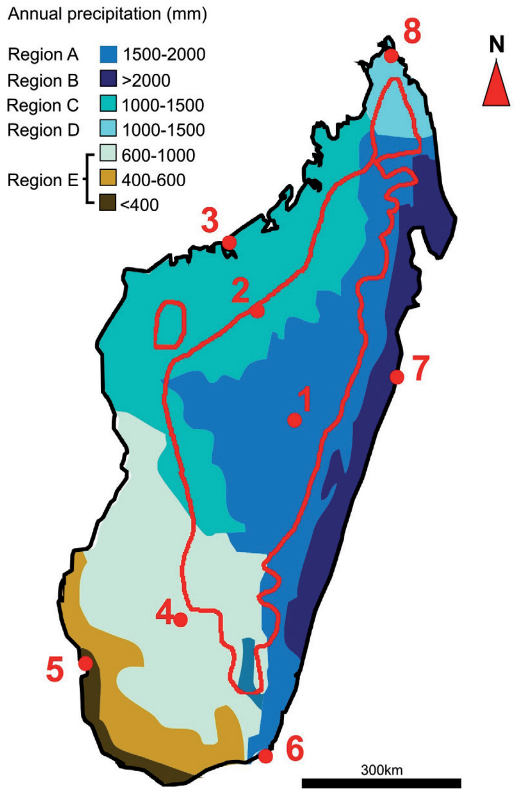

Figure 2. Precipitation map of Madagascar (after ONE, 2008a) with the lavaka-prone area (red line; Cox et al.*, 2010) and our study areas: Antananarivo (Site 1), Maevatanana (Site 2), Majunga (Site 3), Ranohira (Site 4), Toliara (Site 5), Taolagnaro (Site 6), Toamasina (Site 7), Antsiranana (Site 8).*

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Numerous publications mention that climate is controlling the process of lavakization because of the occurrence of heavy rainfalls followed by dry seasons (e.g. Mietton, 2014; Voarintsoa *et al*., 2012). We particularly considered this aspect in our study, in order to understand to what extent the precipitation intensity contributes to the initiation and acceleration of gully formation and development. The aim of this study was to analyse lavaka distribution with GIS methods and to study the relationships between lavaka density and climatic conditions.

2. Climatic features of Madagascar and the effect of precipitation on gully erosion

Madagascar's climatic diversity and varied wildlife is partly caused by its size and NNE-SSW aligned geography extending between 12°S and 23°S. Topography roughly follows this orientation, with highlands in the center of the island. Two different seasons can be distinguished, a drier winter (May-October) and a wet summer (November-April). Climate is determined by the southeastern trade winds in winter and tropical cyclones in summer (Jury, 2003). To describe the local climate regimes, Donque (1972) has divided Madagascar into 5 climate regions. The 1200 m a.s.l. mountain ridge running north-south along the axis of the island (Fig. 2, Region A) causes orographic uplift resulting in a dense tropical rainforest covering the eastern-facing slopes (Fig. 2, Region B), while the west lee-ward part is drier with sparser vegetation (Fig. 2, Region C; Wells, 2003). Rain in the southwest part of the island mainly occurs in summer due to the Mozambique Current (Donque, 1972; Jury, 2003). In the west part of the island most of the annual precipitation is due to tropical storms and falls within a few months (November-April). The northernmost sector of the island (Fig. 2, Region D) experiences an equatorial climate. The winter is dry and warm, and is followed by a hot tropical summer when the Intertropical Convergence Zone (ITCZ) brings tropical thunderstorms. The south and southwest part (Fig. 2, Region E) is dry and mid-latitude air masses are brought by cold fronts (Donque, 1972; Jury, 2003).

Tropical cyclones often hit Madagascar. The north-south ridge can break up their circulation but several cyclones are strong enough to significantly influence the local climate conditions. During these storms a total of 700 mm precipitation can fall in a few days (Jury, 2003).

The spatial variability in the amount of the annual precipitation is remarkable and determines Madagascar's landscape. This variable rainfall pattern is an important factor worldwide when considering land degradation, but also its temporal distribution plays a specific role. Heavy rainfall can increase soil loss, but beside the rainfall intensity and its temporal distribution, the strength of these effects principally depends on lithology and vegetation cover. A number of experiments worldwide showed that the surface roughness and the local topographic gradient distribution are related to sediment yield, and that rainfall intensity sequence influences soil loss (Römkens *et al*., 2001). A variety of studies also showed that afforested slopes are less erodible than bare slopes (Cerdà, 1998). However, "changes in rainfall amount associated with changes in storm rainfall intensity likely have a greater impact on runoff and erosion than simply changes in rainfall amount alone", and erosion is less dependent on canopy cover compared to the erosional effect of storms (Nearing *et al*., 2005).

The periodicity of rainfall intensity is one of the most important factors in soil degradation, especially under the specific conditions of Madagascar soils. Lavakization occurs mainly in areas affected by strong contrasts between dry and wet seasons (Voarintsoa *et al*., 2012). This seasonality causes the degradation of the soils prone to lavakization. During the dry periods cracks appear in the sparsely covered upper soil layer and the intensive rainfall of the wet season could reach the lower unstable soil layer through them (Wells and Andriamihaja, 1993). In this case erosion could initiate a lavaka suddenly within a few days (Cox *et al*., 2004).

Assuming the importance of precipitation on lavaka formation, we studied the spatial and temporal distribution of precipitation in the light of lavakas spatial distribution in order to reveal possible correlations.

3. Data and Methods

In order to relate lavakization and climatic conditions, two datasets have been created: (1) the time series of precipitation at 8 locations have been collected, and (2) satellite images have been evaluated to map lavaka distribution and density. The main criteria was the availability of both kind of data for the same period and same area: areas were selected where the precipitation data has a good temporal coverage and there is an acceptable image control on lavaka appearance. Based on this selection, continuous precipitation data and freely accessible satellite images were available between 2003 and 2008 for 8 areas.

As most of the previous lavaka studies concentrated on the LPA (Raveloson *et al*., 2014), we intended to have a better spatial coverage by including areas with different environmental properties. Therefore, sites were also chosen outside the LPA (Fig. 2). The 8 study areas are Antananarivo (Site 1), Maevatanana (Site 2), Majunga (Site 3), Ranohira (Site 4), Toliara (Site 5), Taolagnaro (Site 6), Toamasina (Site 7), and Antsiranana (Site 8) (Fig. 2).

Evaluation of lavaka distribution for the selected sites was achieved using freely accessible high-resolution satellite imagery (from Google Earth). A total of 800 km^2 has been processed by visual estimation of the images at 1 km × 1 km grid cell scale (each site is 100 km^2 large). Lavakas have been counted in each cell and a semi-quantitative gully appearance map has been created manually for each study area. These maps were then stored using Keyhole Markup Language (KML) files, and transferred into a conventional Geographic Information System (GIS) using Global Mapper 13. The resulting datasets have been examined against several raster and vector data layers representing various landscape variables. Statistical data for slope and elevation have been derived from the SRTM data (CGIAR-CSI, 2014) for each study area, each cell and also each individual lavaka. Further information on the landscape and human activities were acquired based on the visual inspection of the imagery.

Results were compared to the monthly precipitation data to reveal the influence of the contrasting dry and wet seasons. For that purpose statistical tests have been carried out (see below).

Climatic, lithological and other thematic maps helped to understand the link between lavakization and the different factors. Maps showing relevant data of soil (Besairie, 1946), lithology (Du Puy and Moat, 2003), temperature (Cornet, 1972), agroclimatology (Oldeman, 1988), tropical cyclones threatened areas (ONE, 2008b), and precipitation distribution (ONE, 2008a) have been integrated using Global Mapper 13. Specific cyclone track maps (Donque, 1972; Nash *et al.*, 2015) were used to study the erosive effects of heavy rainfall events. The climatic data were downloaded from the National Climatic Data Center of National Oceanic Atmospheric Administration (NOAA, NCDC, 2014) in order to show the inter-annual variability. Daily rainfall measurements were extracted from these databases between 2003 and 2008.

To compare the temporal precipitation distribution of the studied sites, statistical hypothesis tests were carried out. Since the vicinity of Antananarivo (Site 1) is the most typical (and most studied) area of lavaka appearance, this site was also chosen as the reference for the precipitation data. The purpose of the tests was to find out which sites was are similar statistically in terms of monthly precipitation distribution in the studied years (2003-2008). The statistical hypothesis was the following: the amount of precipitation in a given month (e.g., January) at Site N ($N \neq 1$) has the same distribution as Site 1 (Antananarivo). The alternative hypothesis was that they are not the same. Since we have detailed data for only six years for all the sites and some monthly data still missing, the normality of the distributions of the monthly precipitation data cannot be proven due to the low number of observations (maximum 6, but sometimes as low as 4). Consequently, Mann-Whitney (nonparametric) tests have been carried out to reveal the statistical similarities/differences in monthly precipitation data with respect to the temporal precipitation distribution of Antananarivo (Site 1), using the web-implementation of Lowry (2015).

4. Results

4.1. Analysing lavaka distribution

Visualization of imagery showed that the studied areas have lavaka densities between 0 and 4.3 km^{-2}. A total of 670 lavakas have been counted in four sites of the study areas: Antananarivo (Site 1), Maevatanana (Site 2), Majunga (Site 3), and Ranohira (Site 4), while the other four areas do not contain lavakas at all (Figs. 3 to 6). The average lavaka density for Sites 1-4 is 1.7 km^{-2} (which is similar to data mentioned by Voarintsoa *et al.* (2012) and Raveloson *et al.* (2013): 2.2-2.9 km^{-2}). Maevatanana was the most gullied area with a total of 427 lavakas and an average of 4.3 km^{-2}. Maximum lavaka density here was 23 km^{-2}. This is less than maximum lavaka density of 30 km^{-2} published by Wells *et al.* (1991), and much below the values of 50-150 km^{-2} of Voarintsoa *et al.* (2012) (Table 1).

Table 1. Characteristics of Site 1 to 4 (where lavakas have been detected). (Mean, minimum and maximum elevation [m], slope angle data [°]; lavaka density [nr km-2]; total lavaka number per site; percent of non-gullied areas and percent of areas with more than 5 and 15 lavakas per km²).

Site characteristics					
		1	**2**	**3**	**4**
Elevation (m)	Mean	1 260	225	51	1 001
	Max	1 452	336	113	1 083
	Min	1 144	124	1	923
Slope angle (°)	Mean	7.9	4.9	2.5	2.8
	Max	31.2	20.9	16.2	9.9
Lavaka (nr km^{-2})	Mean	1.8	4.3	0.1	0.5
	Max	17	23	6	8
Lavaka (nr site^{-1})		181	427	12	50
Non-gullied area (%)		52	28	95	82
>5 lavaka km^{-2} (%)		10.0	10.2	0.4	2.0
>15 lavaka km^{-2} (%)		1.0	2.4	0.0	0.0

In each study area where lavakas were found (Sites 1-4), gully presence for each cell varied greatly. Most of the cells do not contain gullies (52% for Site 1; 28% for Site 2; 95% for Site 3 and 82% for Site 4). Less than 10 % of the cells contained more than 5 lavakas (10% for Site 1; 10% for Site 2; 0.4% for Site 3; 2% for Site 4) and less than 1% reached the density of 15 km^{-2} (Table 1; Figs. 3 to 6).

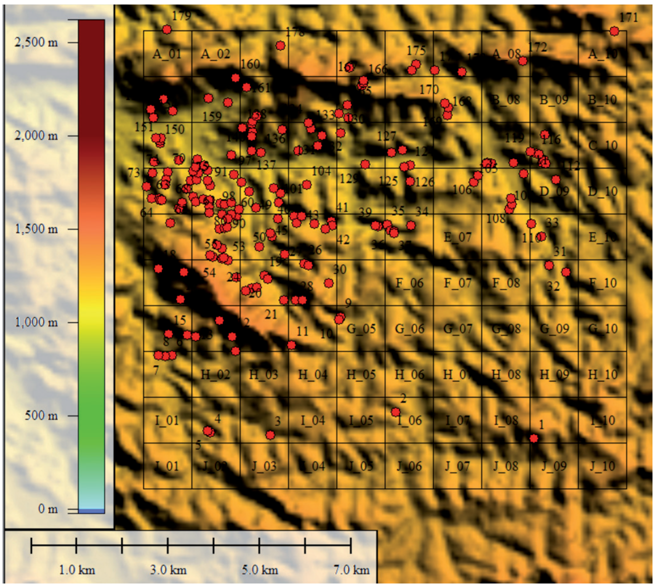

Figure 3. Lavaka distribution in Site 1 (Antananarivo). Lavakas are marked with red dots.

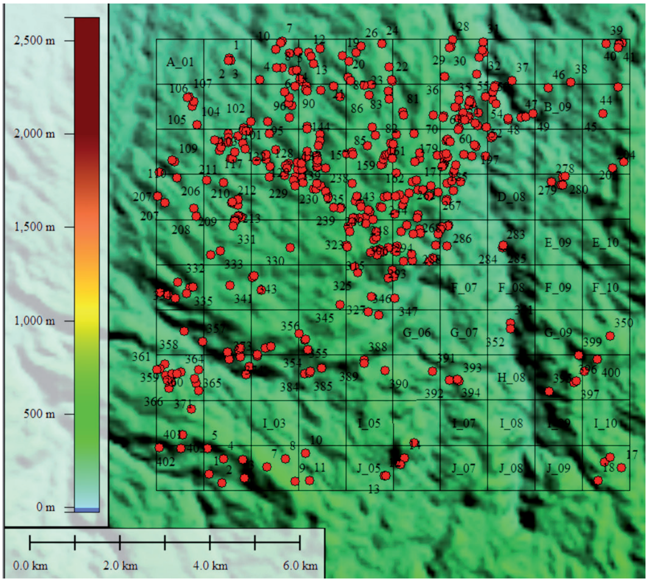

Figure 4. Lavaka distribution in Site 2 (Maevatanana). Lavakas are marked with red dots.

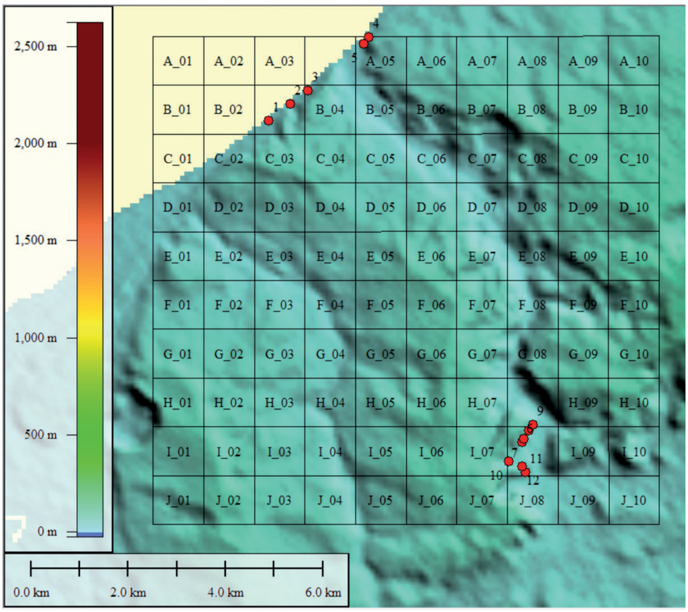

Figure 5. Lavaka distribution in Site 3 (Majunga). Lavakas are marked with red dots.

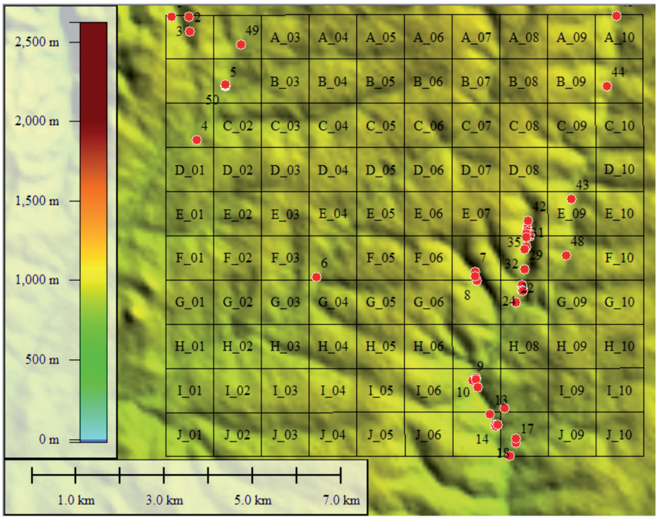

Figure 6. Lavaka distribution in Site 4 (Ranohira). Lavakas are marked with red dots.

Average gradients of slopes affected by lavakas differ slightly from one site to another, although it does not exceed 10°. In contrast to previously published studies (e.g. Mulder and Idoe, 2004; Voarintsoa *et al*., 2012), lavakas were found on lower elevation areas (the lowest lavaka occurs at 9 m a.s.l.) and on gentle slopes (minimum gradient: 0.6°) (Table 2; Fig. 7; Fig. 8). However, as gradient and elevation data were derived from the SRTM data having a resolution of ca. 90 m, the gradients are often underestimated.

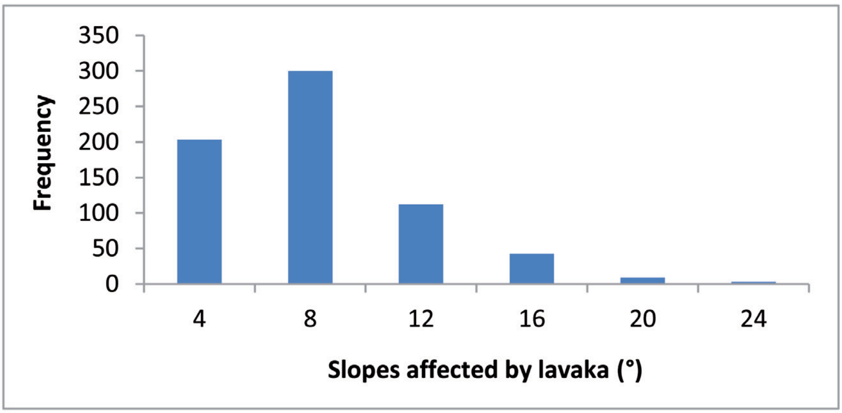

Figure 7. Frequency distribution of slopes affected by lavakas.

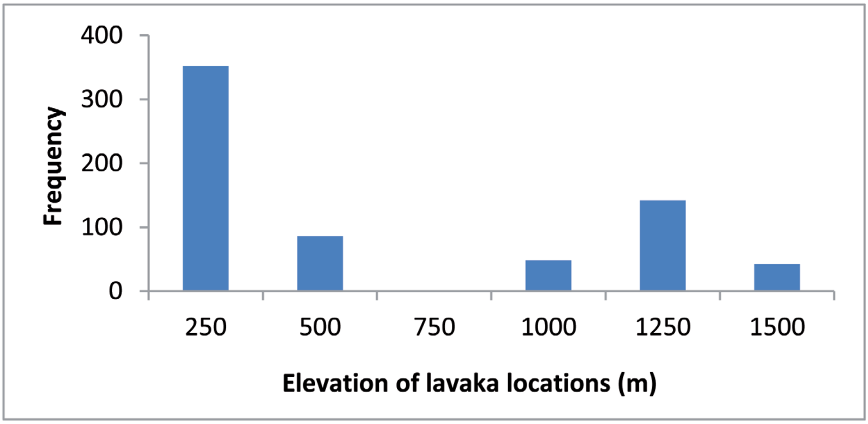

Figure 8. The altitude distribution of lavaka locations.

Table 2. Mean, minimum and maximum elevation and slope angle of lavaka location in Sites 1 to 4.

Lavaka occurrence					
		1	2	3	4
Elevation (m)	Mean	1 223	200	26	965
	Max	1 364	262	44	1 007
	Min	1 151	130	9	928
Slope angle (°)	Mean	9.8	5.0	5.9	4.1
	Max	22.0	16.1	8.9	7.1
	Min	3.2	0.6	2.5	2.0

4.2. Processing of meteorological data

Climatic data of Madagascar reveal that temperature varies typically with altitude, while the precipitation distribution shows more diverse patterns. Antananarivo (Site 1: 18°56’S 47°31’E) and Maevatanana (Site 2: 16°57-S 46°50’E) are located in the LPA. In both areas the geomorphological and meteorological conditions are similar to those of Majunga (Site 3: 15°43’S 46°19’E), located in the western coast of the island. These three areas are characterized by sparse or almost completely lacking vegetation and annual precipitation of 1000-1500 mm falling mainly in summer (January to March). Ranohira (Site 4: 22°26’S 45°21’E) is close to the LPA with an annual precipitation of 600-1000 mm.

Toliara (Site 5: 23°21'S 43°40'E) is the driest site of the study areas, with less than 400 mm annual precipitation. Ranohira (Site 4) and Toliara (Site 5) are characterized by sandy soils covered with open shrub patches. Taolagnaro (Site 6: 25°02'S 46°59'E) is located in the southeast corner of the island. It has a particular local climate due to the orographic influence. Its western part is one of the driest areas of the country while the eastern one is part of the humid eastern belt with more than 2000 mm annual precipitation. The wettest of our study areas are Toamasina (Site 7: 18°09'S 49°25'E) and Antsiranana (Site 8: 12°16'S 49°17'E). In both sites the average annual precipitation is approximately 2000 mm, although Toamasina (Site 7) is rainy throughout the whole year while in Antsiranana (Site 8) the precipitation mainly occurs in summer, when the tropical cyclones are frequent.

To show the connection between lavaka distribution and climatic elements, the local characteristics were collected and summarized in a table using the data of the maps (Table 3), and statistical tests were carried out to compare the precipitation distributions. Table 3 includes the climatic conditions: average temperatures, percentage of rainy days, annual precipitation, specific cyclone tracks (Donque, 1972; ONE, 2008b; Nash *et al.*, 2015). Data for vegetation cover, soil, lithology and land use intensity were also collected. The last three columns contain the calculated lavaka density in 2003 and 2008, and the difference of these two values. The results of the daily precipitation data collection were summarized in diagrams.

The eight precipitation diagrams between 2003 and 2008 confirmed the results of the map analysis (Figs. 9 to 16). The diagrams show the distribution of the precipitation and represent the strength of the alternation between the dry and wet seasons. The maps show only average rainfall amounts and do not include the outliers appeared in the monthly precipitation data. These outliers are caused by tropical cyclones (TC) that brought few hundred mm of rainfall over a few days (e.g.: TC Elita, TC Ernest, TC Felapi, TC Gafilo, TC Indlala, TC Fame, TC Ivan; NASA, 2014; Figs. 9 to 16).

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Table 3. Lavaka density (for 2003 and 2008) in relation to various environmental characteristics. Cyclone track types were defined using Nash et al. (2015) classification.

	Climatic data				Other influencing factors				Lavaka density (nr km^{-2})		
	Average temperature (°C)	**Rainy days (%)**	**Precipitation (mm yr^{-1})**	**Cyclone track types**	**Vegetation cover**	**Soil**	**Lithology**	**Land use**	**2003**	**2008**	**Change**
1. Antananarivo	7-10	~38	1 000-1 500	II,III	sparse	laterite	granites	intensive	1.81	1.81	no
2. Maevatanana	16-18	~38	1 000-1 500	II,III	sparse	red sand	sandstones	no	4.27	4.27	no
3. Majunga	>18	~25	1 000-1 500	II	sparse	red clay	limestones	no	0.15	0.17	0.02
4. Ranohira	>10	<21	600-1 000	I,II	sparse	red sand	sandstones	no	0.5	0.5	no
5. Toliara	<15	<21	<400	I	sparse	sand	unconsolidated sand	intensive	0	0	no
6. Taolagnaro	16-18	>70	>2 000	I-IV	forest	sand	granites	no	0	0	no
7. Toamasina	16-18	>70	>2 000	III,IV	dense forest	laterite	sandstones	intensive	0	0	no
8. Antsiranana	16-18	~25	1 500-2 000	I,II	sparse	clay	limestones	intensive	0	0	no

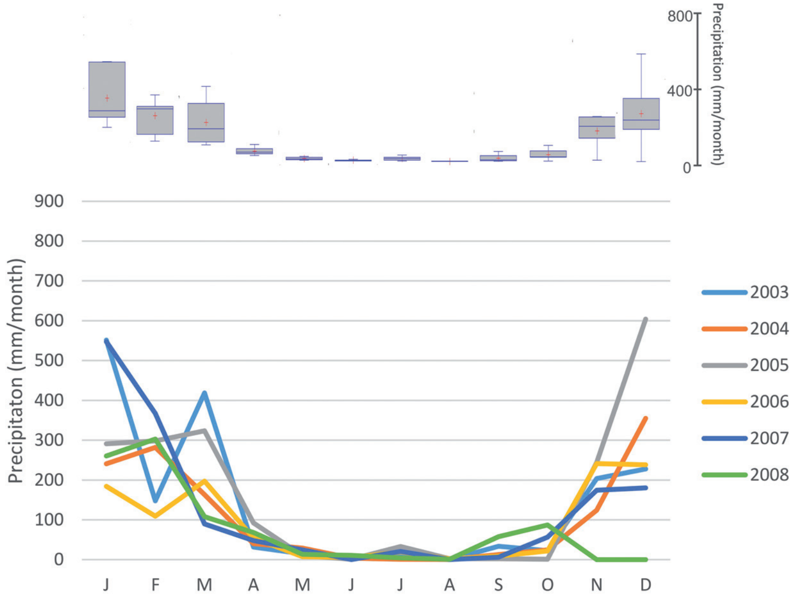

Figure 9. Monthly precipitation data for Site 1 (Antananarivo) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

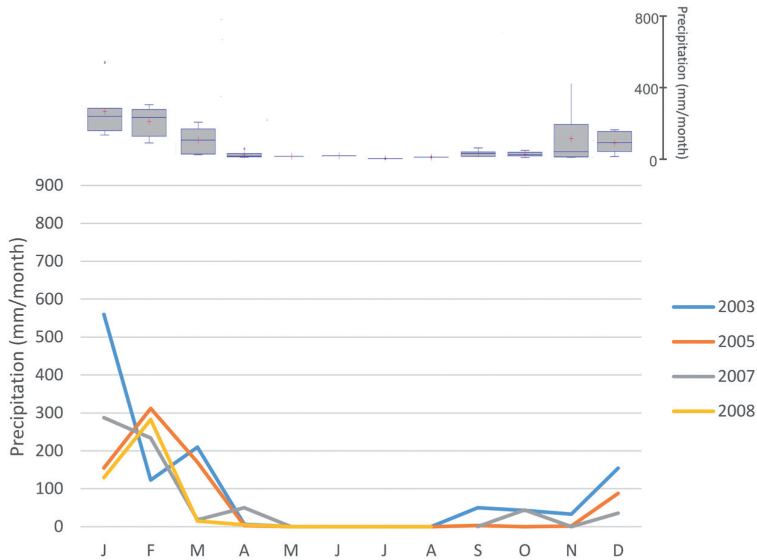

Figure 10. Monthly precipitation data for Site 2 (Maevatanana) in 2003, 2005, 2007, 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

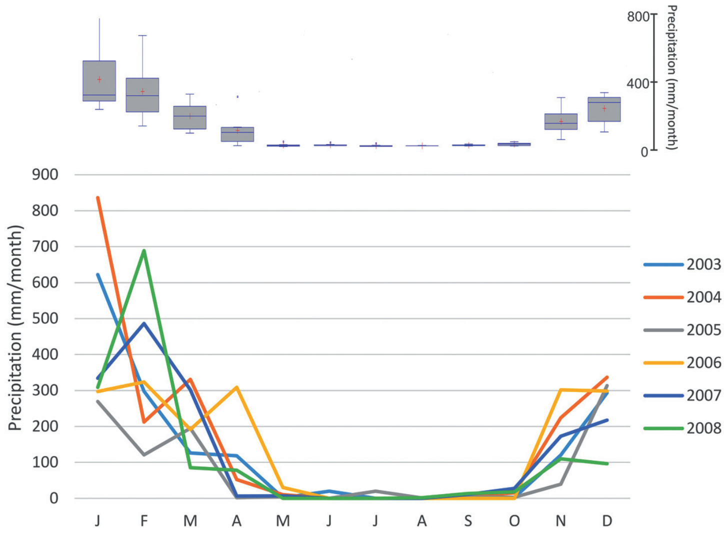

Figure 11. Monthly precipitation data for Site 3 (Majunga) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

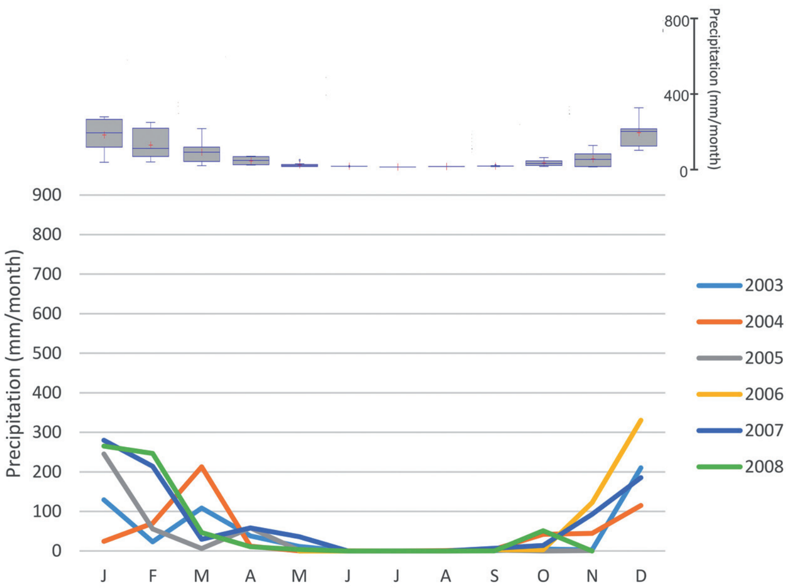

Figure 12. Monthly precipitation data for Site 4 (Ranohira) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

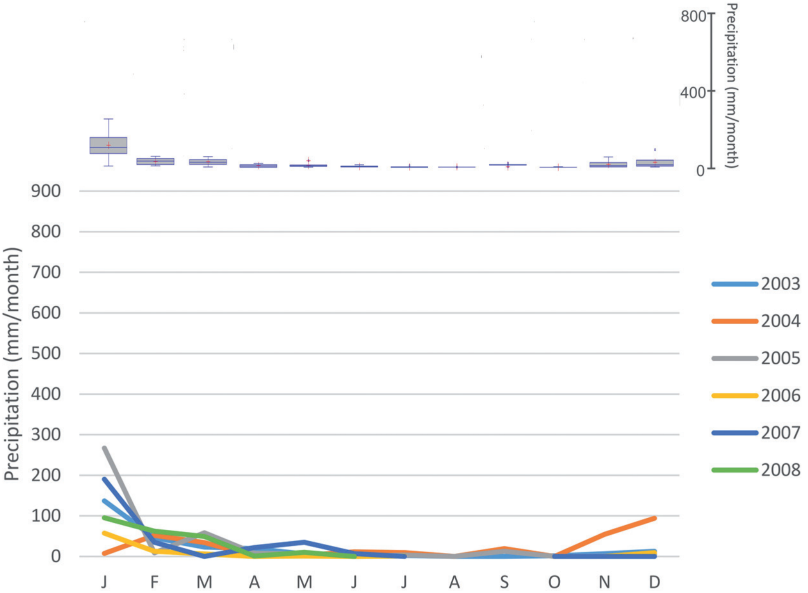

Figure 13. Monthly precipitation data for Site 5 (Toliara) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

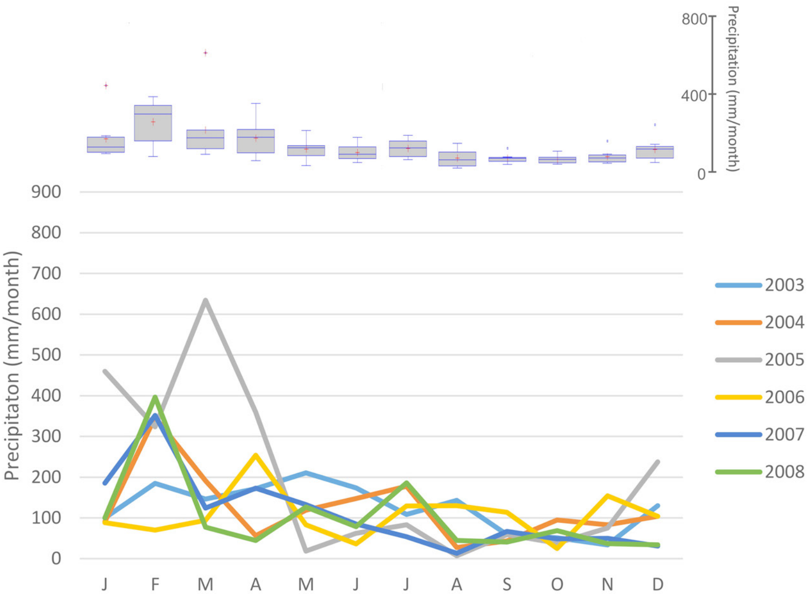

Figure 14. Monthly precipitation data for Site 6 (Taolagnaro) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

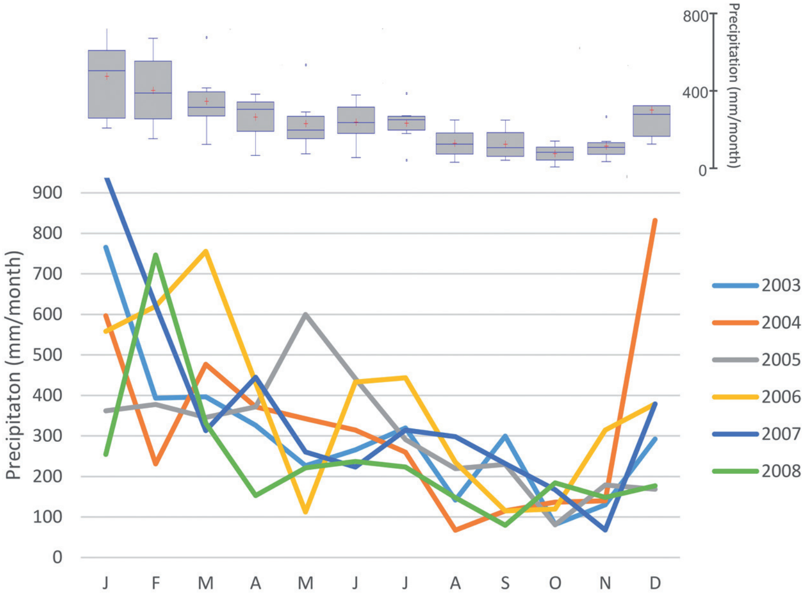

Figure 15. Monthly precipitation data for Site 7 (Toamasina) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

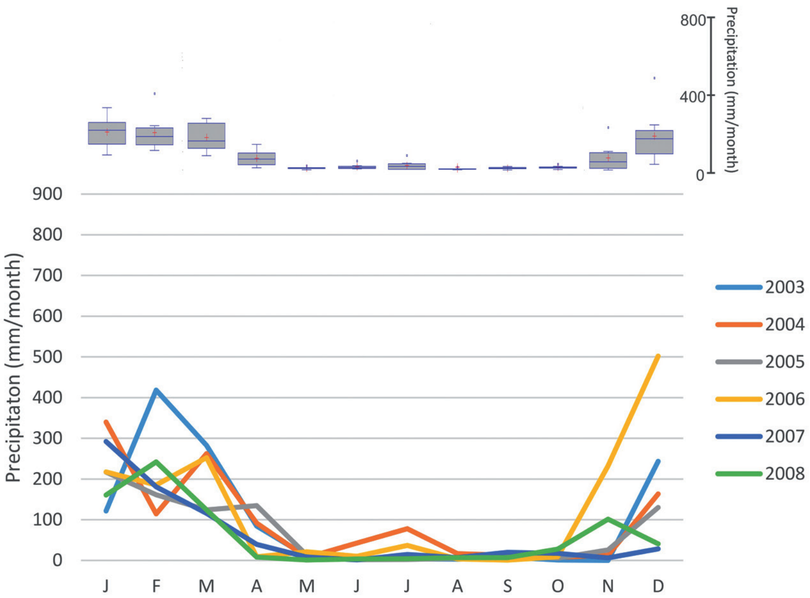

Figure 16. Monthly precipitation data for Site 8 (Antsiranana) from 2003 to 2008 (NOAA, NCDC, 2014) with box-whisker plots showing the variation of precipitation for each month.

For comparison, box-whisker plots of the monthly data are shown on the charts. The seasonal variability of precipitation is stronger where 1500 mm precipitation falls in less than 4-5 months. Conversely, the seasonal variability is lower where the ratio of rainy days is around 70%.

As the results of the Mann-Whitney tests show (Fig. 17), the precipitation pattern of the dry season (May to August) is mostly statistically dissimilar in all sites in relation to Antananarivo (Site 1). Therefore these values cannot be used for comparative studies. In terms of statistical dissimilarity, Sites 6-8 correspond to sites where no lavakas are found. Toliara (Site 5) precipitation data are significantly different from that of the reference site in almost each month. Toamasina (Site 7) shows statistically significant difference in behaviour compared to Site 1, except for November and December. The same can be stated for Taolagnaro (Site 6), except for December, February and March. However, Antsiranana (Site 8) shows statistically similar precipitation values as Antananarivo, which is a somewhat unexpected result. Considering the sites with lavaka occurrences (Sites 2, 3, 4), which are expected to show similarity to Site 1, they mostly fulfil this expectation. Majunga (Site 3) follows the behaviour of Site 1 (the differences in all summer months are statistically insignificant), and this is also true for Maevatanana (Site 2) except for December. Ranohira (Site 3) is similar in the wet season, except for November and February.

Site Nr.	Site	J	F	M	A	M	J	J	A	S	O	N	D
2.	Maevatanana				■	■	■	■	■				■
3.	Majunga					■	■	■					
4.	Ranohira		■				■	■	■	■		■	
5.	Toliara	■	■	■	■	■		■	■		■	■	■
6.	Taolagnaro	■			■	■	■	■	■	■		■	
7.	Toamasina	■	■	■	■	■	■	■	■	■	■		
8.	Antsiranana								■				

Figure 17. Summary diagram of Mann-Whitney hypothesis tests for monthly precipitation data. Grey boxes indicate the statistically significant (at level 0.05) differences of Antananarivo (Site 1) precipitation data and that of the respective sites. Empty spaces indicate those comparisons, where the hypothesis of similarity cannot be rejected. The detailed analysis results are tabulated in Appendix A.

These results are in good congruence with the presence/absence of lavakas, except for Site 8, which shows similar precipitation values as Antananarivo, though at Antsiranana no lavakas were found. This observation can be explained by the fact that lavakization is the result of multifactorial environmental conditions, and many other factors can play a role in the occurrence of lavakas apart from climatic factors.

The statistically significant differences in the wet season were verified for the sites without lavakas, whereas for lavaka-bearing areas the differences are typically statistically not significant (excluding a few months at various sites).

Comparison of lithology, soil and land use with the lavaka density cannot explain the presence or absence of lavakas at the studied sites. In fact, lavakas occur in both intensively and extensively managed areas. Also, the presence or absence of lavakas is not discernible based on soil and lithology data. Inclusion of precipitation data in the analysis improved the categorisation leading us to the conclusion that lithology and soil are less important than the distribution of the precipitation.

Besides the quantity and temporal distribution of precipitation, plant cover is also similar in Antananarivo (Site 1), Maevatanana (Site 2) and Majunga (Site 3). Despite the fact that the annual rainfall is lower in Ranohira (Site 4), this area is also similar to the first three in precipitation intensity and vegetation cover. As it was mentioned earlier, the most intense precipitation events are often related to tropical cyclones (TCs). Of the study areas characterized by high lavaka density, Ranohira (Site 4) is affected by TC tracks Type I, Majunga (Site 3) is affected by TC tracks Types I and II, whereas Sites 2, 3 and 4 are affected by TC track Types II and III (using the typology of Donque, 1972; ONE, 2008b; Nash *et al*., 2015).

5. Conclusions

The analysis of the temporal precipitation pattern of 8 study sites selected in Madagascar has revealed a possible correlation with the development of lavakas. Lavakas were found only in 4 of 8 study areas, where the precipitation intensity and other regional characteristics are similar. According to our analysis, the alternation of dry and wet seasons is highly characteristic in these four sites, whereas in the other four sites the precipitation distribution is significantly different. No lavakas were found in densely vegetated areas where the precipitation is high throughout the year, and in Toliara where the precipitation is one of the lowest in Madagascar throughout the year. We conclude that this is due to the lack of alternation of wet and dry periods. Results of lavaka counting using satellite imagery showed that lavaka density has increased only in the coastal region of Majunga in a few square kilometres between 2003 and 2008. We speculate that this increase might be in connection with the fact that Majunga was hit by several tropical cyclones.

The possible relationship between the temporal distribution of precipitation and the development, and particularly the density, of lavakas, support our assumption that the high amount but uneven yearly distribution of precipitation is one of the main factors governing lavaka formation. We assume, provided that other factors (e.g., lithology) are present, an additional factor that may increase the probability of lavaka development is the appearance of tropical cyclones delivering high amounts of rainfall in a few days. Further studies are needed to verify these assumptions in detail.

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Appendix. Detailed results of nonparametric Mann-Whitney tests (used implementation of Lowry (2015)). The assumed statistical hypothesis was that the distribution of precipitation data of a given month of a given site compared to that of Antananarivo (Site 1) is not different at the given significance level (0.05). The rows in bold indicate statistically significant differences. U_A: computed Mann-Whitney test statistics; ns: non-significant differences.

	Sites	Significance	U_A	Lower limit	Upper limit	z	p_1	p_2	Mean ranks	
January	Maevatanana	ns	9	3	21	---	---	---	6	4.8
	Majunga	ns	18	7	29	0.08	0.4681	0.9362	6.5	6.5
	Ranohira	ns	8	5	25	1.19	0.117	0.234	7.2	4.6
	Toliara	**0.05**	**4**	**7**	**29**	**2.16**	**0.0154**	**0.0308**	**8.8**	**4.2**
	Taolagnaro	**0.05**	**5**	**7**	**29**	**2**	**0.0228**	**0.0455**	**8.7**	**4.3**
	Toamasina	**0.05**	**30**	**7**	**29**	**-1.84**	**0.0329**	**0.0658**	**4.5**	**8.5**
	Antsiranana	ns	10	7	29	1.2	0.1151	0.2301	7.8	5.2
February	Maevatanana	ns	11	3	21	---	---	---	5.7	5.3
	Majunga	ns	23	7	29	-0.72	0.2358	0.4715	5.7	7.3
	Ranohira	**0.05**	**4**	**5**	**25**	**1.92**	**0.0274**	**0.0549**	**7.8**	**3.8**
	Toliara	**0.05**	**0**	**7**	**29**	**2.8**	**0.0026**	**0.0051**	**9.5**	**3.5**
	Taolagnaro	ns	23	7	29	-0.72	0.2358	0.4715	5.7	7.3
	Toamasina	**0.05**	**32**	**7**	**29**	**-2.16**	**0.0154**	**0.0308**	**4.2**	**8.8**
	Antsiranana	ns	15	7	29	0.4	0.3446	0.6892	7	6
March	Maevatanana	ns	4	3	21	---	---	---	6.8	3.5
	Majunga	ns	17	7	29	0.08	0.4681	0.9362	6.7	6.3
	Ranohira	ns	6	5	25	1.55	0.0606	0.1211	7.5	4.2
	Toliara	**0.05**	**0**	**7**	**29**	**2.8**	**0.0026**	**0.0051**	**9.5**	**3.5**
	Taolagnaro	ns	14	7	29	0.56	0.2877	0.5755	7.2	5.8
	Toamasina	**0.05**	**31**	**7**	**29**	**-2**	**0.0228**	**0.0455**	**4.3**	**8.7**
	Antsiranana	ns	18	7	29	0.08	0.4681	0.9362	6.5	6.5
April	**Maevatanana**	**0.05**	**3**	**5**	**25**	**2.1**	**0.0179**	**0.0357**	**8**	**3.6**
	Majunga	ns	20	7	29	-0.24	0.4052	0.8103	6.2	6.8
	Ranohira	ns	9	5	25	1	0.1587	0.3173	7	4.8
	Toliara	**0.05**	**0**	**7**	**29**	**2.8**	**0.0026**	**0.0051**	**9.5**	**3.5**
	Taolagnaro	**0.05**	**30**	**7**	**29**	**-1.84**	**0.0329**	**0.0658**	**4.5**	**8.5**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	ns	17	7	29	0.08	0.4681	0.9362	6.7	6.3

	Sites	Significance	U_A	Lower limit	Upper limit	z	p_1	p_2	Mean ranks	
May	**Maevatanana**	**0.05**	**0**	**5**	**25**	**2.65**	**0.004**	**0.008**	**8.5**	**3**
	Majunga	**0.05**	**7**	**7**	**29**	**1.68**	**0.0465**	**0.093**	**8.3**	**4.7**
	Ranohira	ns	8	7	29	1.52	0.0643	0.1285	8.2	4.8
	Toliara	**0.05**	**7**	**7**	**29**	**1.68**	**0.0465**	**0.093**	**8.3**	**4.7**
	Taolagnaro	**0.05**	**34**	**7**	**29**	**-2.48**	**0.0066**	**0.0131**	**3.8**	**9.2**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	ns	9	7	29	1.36	0.0869	0.1738	8	5
June	**Maevatanana**	**sig**	**0**	**3**	**21**	**---**	**---**	**---**	**7.5**	**2.5**
	Majunga	**0.05**	**6**	**7**	**29**	**1.84**	**0.0329**	**0.0658**	**8.5**	**4.5**
	Ranohira	**0.05**	**1**	**7**	**29**	**2.64**	**0.0041**	**0.0083**	**9.3**	**3.7**
	Toliara	ns	13	7	29	0.72	0.2358	0.4715	7.3	5.7
	Taolagnaro	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	ns	21.5	7	29	-0.48	0.3156	0.6312	5.9	7.1
July	**Maevatanana**	**0.05**	**0.5**	**5**	**25**	**2.56**	**0.0052**	**0.0105**	**8.4**	**3.1**
	Majunga	**0.05**	**4**	**7**	**29**	**2.16**	**0.0154**	**0.0308**	**8.8**	**4.2**
	Ranohira	**0.05**	**0**	**5**	**25**	**2.65**	**0.004**	**0.008**	**8.5**	**3**
	Toliara	**0.05**	**5**	**5**	**25**	**1.73**	**0.0418**	**0.0836**	**7.7**	**4**
	Taolagnaro	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	ns	18	7	29	0.08	0.4681	0.9362	6.5	6.5
August	**Maevatanana**	**sig**	**1.5**	**2**	**16**	**---**	**---**	**---**	**6.3**	**2.5**
	Majunga	ns	11	7	29	1.04	0.1492	0.2983	7.7	5.3
	Ranohira	**0.05**	**5**	**5**	**25**	**1.73**	**0.0418**	**0.0836**	**7.7**	**4**
	Toliara	**sig**	**1.5**	**2**	**16**	**---**	**---**	**---**	**6.3**	**2.5**
	Taolagnaro	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
September	Maevatanana	ns	10	5	25	0.82	0.2061	0.4122	6.8	5
	Majunga	ns	9	7	29	1.36	0.0869	0.1738	8	5
	Ranohira	**0.05**	**5**	**7**	**29**	**2**	**0.0228**	**0.0455**	**8.7**	**4.3**
	Toliara	ns	8	2	16	---	---	---	5.2	4.7
	Taolagnaro	**0.05**	**34**	**7**	**29**	**-2.48**	**0.0066**	**0.0131**	**3.8**	**9.2**
	Toamasina	**0.05**	**36**	**7**	**29**	**-2.8**	**0.0026**	**0.0051**	**3.5**	**9.5**
	Antsiranana	ns	15.5	7	29	0.32	0.3745	0.749	6.9	6.1

	Sites	Significance	U_A	Lower limit	Upper limit	z	p_1	p_2	Mean ranks	
October	Maevatanana	ns	1	7	29	.04	.1492	.2983	77.7	4.9
	Majunga	ns	8	7	29	1.52	0.0643	0.1285	8.2	6
	Ranohira	ns	11	7	29	1.04	0.1492	0.2983	7.7	**4.4**
	Toliara	**0.05**	**1**	**5**	**25**	**2.46**	**0.0069**	**0.0139**	**8.3**	**3.8**
	Taolagnaro	ns	27	7	29	-1.36	0.0869	0.1738	5	**4.7**
	Toamasina	**0.05**	**34**	**7**	**29**	**-2.48**	**0.0066**	**0.0131**	**3.8**	6.2
	Antsiranana	ns	9	7	29	1.36	0.0869	0.1738	8	4.9
November	Maevatanana	ns	9.5	5	25	0.91	0.1814	0.3628	6.9	4.9
	Majunga	ns	15	7	29	0.4	0.3446	0.6892	7	6
	Ranohira	**0.05**	**5.5**	**7**	**29**	**1.92**	**0.0274**	**0.0549**	**8.6**	**4.4**
	Toliara	**0.05**	**4**	**5**	**25**	**1.92**	**0.0274**	**0.0549**	**7.8**	**3.8**
	Taolagnaro	**0.05**	**7**	**7**	**29**	**1.68**	**0.0465**	**0.093**	**8.3**	**4.7**
	Toamasina	ns	16	7	29	0.24	0.4052	0.8103	6.8	6.2
	Antsiranana	ns	8.5	7	29	1.44	0.0749	0.1499	8.1	4.9
December	**Maevatanana**	**0.05**	**5**	**5**	**25**	**1.73**	**0.0418**	**0.0836**	**7.7**	**4**
	Majunga	ns	19	7	29	-0.08	0.4681	0.9362	6.3	6.7
	Ranohira	ns	9	3	21	---	---	---	6	4.8
	Toliara	**0.05**	**4.5**	**5**	**25**	**1.83**	**0.0336**	**0.0673**	**7.8**	**3.9**
	Taolagnaro	ns	8	7	29	1.52	0.0643	0.1285	8.2	4.8
	Toamasina	ns	22	7	29	-0.56	0.2877	0.5755	5.8	7.2
	Antsiranana	ns	13	7	29	0.72	0.2358	0.4715	7.3	5.7