# Human induced dust in Aruba

## An assessment of the transport and spatial deposition dynamics of dust from off-road driving in Aruba and the effect of driving speed and traffic density

**MSc thesis by Teun Vogel**

**June 2017**

Soil Physics and
Land Management Group

WAGENINGEN UNIVERSITY
WAGENINGEN UR

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*An assessment of the transport and spatial deposition dynamics of dust from off-road driving in Aruba and the effect of driving speed and traffic density*

Master thesis Soil Physics and Land Management Group submitted in partial fulfilment of the degree of Master of Science in International Land and Water Management at Wageningen University, the Netherlands

**Study program:**
MSc International Land and Water Management

**Student registration number:**
930123901070

**SLM 80336**

**Supervisors:**
WU Supervisor: Klaas Metselaar and Michel Riksen
Host supervisor: Emil ter Horst

**Examinator:**
Prof. Coen Ritsema

**Date:**
30/06/17

**Soil Physics and Land Management Group, Wageningen University**

## ABSTRACT

Off-road driving has a range of impacts on the environment and human health. In Aruba, traffic on dirt roads and recreational off-road driving has put nature and environment under high pressure. However, the exact effect and dust cloud dimensions, i.e. dust transport and deposition patterns, have not yet been assessed. Furthermore, the effect of different driving speeds and traffic densities on the dust cloud dimensions have not yet been established. Measurements were done to analyse dust transport and spatial deposition along an off-road track, using Modified Wilson And Cooke (MWAC) catchers and placing Inverted Frisbee Dust Deposition (IFDD) catchers in a transect, up to 300 m from the source. In addition, experiments were set up using a quad to measure the effect on dust transport and spatial dust deposition for increasing the driving speed and traffic density. Dust deposition is shown to decrease rapidly with distance from the source, but remains more or less constant from 200 m onwards. Increasing the traffic density results in a slight decrease in deposition per pass, but shows an exponential increase of dust transport. Increasing the driving speed increased dust transport exponentially: 1.71, 2.72 and 5.07 g $m^{-1}$ per pass for 10, 25 and 45 kmph respectively. The dust deposition increased more than linear: 3.55, 5.74, 7.74 g $m^{-1}$ per pass between 15 and 50 m from the source for 10, 20 and 45 kmph respectively. Driving faster on the dirt or off-roads in Aruba thus results in an increase in production of dust per vehicle kilometre travelled (vkt), which is most probably undesirable with regard to the environment and human health. The trade winds blowing predominantly from East can carry the dust far inland, which may have an effect on the health risk of people living downwind from the off-road tracks.

Keywords: off-road driving; dust transport; dust deposition; Modified Wilson And Cooke (MWAC) catcher; Inverted Frisbee Dust Deposition (IFDD) catcher.

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# 1. INTRODUCTION

Recreational off-road driving is an activity that has increased rapidly on all continents (Goossens and Buck, 2014) and still a dramatic increase in popularity is noticeable (Jones et al., 2013). This dirt road and off-road driving can have negative effects, of which for example the impact on the environment has already been recognized for over 80 years (Bates, 1935). It is shown that the off-road vehicular (ORV) activities cause a range of impacts as for example soil erosion and compaction (Buckley, 2004), wind erosion (Goossens and Buck, 2008), damage to vegetation and soil life (Kutiel et al., 1999; Kutiel et al., 2000; Lovich and Bainbridge, 1999; Buckley, 2004; Bates, 1935; Priskin, 2004; Liddle and Greig-Smith, 1975), damage to beach and beach life (Priskin, 2003; Cater et al., 2008; Kelly, 2013) and water and air pollution (Buckley, 2004). Especially air pollution can have a strong negative effect on the health of people and soil life around the dirt roads (Etyemezian et al., 2004; Kuhns et al., 2010; Nolet and van der Veen, 2009; Goossens and Buck, 2011; Soukup et al., 2012). Given the above, the impact of off-road driving on wind erosion has not received the attention it deserves, whereas the impact of agricultural activities on wind erosion have already been the subject of research and show the effect of various tillage practices on the extent of wind erosion (Riksen and Visser, 2008; Masri et al., 2015; Çarman et al., 2016; Gao et al., 2016; Smoyer-Tomic et al., 2004). To our best knowledge, the spatial deposition pattern is not known yet, as well as the transport flux as a result of off-road driving. In addition, the relation with driving speed and traffic density is not known.

For Aruba, tourism constitutes the most important revenue (Gable, 1997), even more than for example Jamaica in terms of percent of the gross national income (ECLAC, 2011). Tourism is such a large sector, that nature and environment have become under high pressure, because all the tourists that visit the country require the construction of hotels and resorts, but also the infrastructure and activities to assure full-time entertainment (Beke, 2016). Off-road vehicular activities are one of the main tourist attractions, especially during the high season from November till May (Beke, 2016). Several tour operators offer trips throughout the island with off-road vehicles as buggies, quads, all-terrain vehicles (ATV's), utility task vehicles (UTV's) or side-by-sides, but also with jeeps and even buses. The enormous demand for these trips result in large rows of off-road vehicles that pass the dirt road and off-road tracks every day, especially along the Northern coast.

The long drought periods that can occur in Aruba, and may increase in the future (ECLAC, 2011), co-occur with an increase in the effects of ORV activities (Nolet and van der Veen, 2009; Beke, 2016; Smoyer-Tomic et al., 2004). For that reason there is an urgent need for a proper management of these activities (Webb et al., 1978; Trantor and Lowes, 2009; Beke, 2016). Due to the negative impact on the environment, off-road vehicles have been partially excluded from a number of national parks globally (Kaaber, 2017; SEPA, 2017). The pressure on the environment in Aruba and the focus on economy and financial income make that the risk exists of degradation for several areas as a result of off-road driving (Oosterhuis, 2016). In order to have a more sustainable management in the future, off-road drivers, governments and park managers should realize that environmental degradation impacts health at all levels including psychological and economic (Trantor and Lowes, 2009).

## 1.1 Problem statement and research design

Off-road driving can have an impact on the environment and on human health. Since Aruba is an island where ORV activities are mostly undertaken by tourists, the impact on dust transport and deposition is likely to be present, but the actual effects are not known yet. In addition, the spatial deposition pattern of dust clouds are not yet assessed, although this information could give new insights in the concentration and deposition fluxes more distant from the source. To our best knowledge, the potential effect on human health in Aruba has not received the attention it deserves, although the concentration rates could exceed the allowed norms. Finally, knowledge on the effect of different driving speeds and traffic densities on the rates of dust transport and spatial deposition is incomplete.

Given the issues of dust produced by off-road vehicles, the dust transport and deposition by average off-road vehicular activities in Aruba and the concentration as parameter of a potential health risk were investigated. Measuring the deposition of dust was included as it can give a clear overview of the distribution pattern as a function of distance. To come up with absolute values, the efficiency factor of the used catchers was taken into account. In addition, the impact of the parameters traffic density and vehicle driving speed was investigated in experiments using a quad as example of an off-road vehicle.

## 2. THEORY

### 2.1 Dust transport and deposition

Wind erosion requires three steps: detachment, transport and deposition. Dust emission is the fraction of wind erosion that is non-natural, being produced for example by an off-road vehicle. Although dust emission differs from wind erosion in various ways, these three steps can still be recognized. An off-road vehicle exerts a certain amount of energy on the soil which starts the detachment. As a result, the dust is transported until it deposits. The transport can take place in the form of creep, saltation or suspension. Suspension is the fraction of sediment that is transported over a larger distance, up to thousands of kilometres. One side effect of these very small particles is that they can potentially affect the health of people (Goossens and Buck, 2014). Whereas most research in the field of wind erosion research is about natural wind erosion, some more recent research also focuses on the enhanced wind erosion by human activities as for example off-road driving. Heavy off-road vehicle (ORV) use has been shown to increase wind erosion (Lovich and Bainbridge, 1999) which is for some soil textures attributed to a decrease of the deflation threshold of the soil (Goossens and Buck, 2008). The deflation threshold is the critical wind condition at which the wind erosion starts for different soils. Taking the soil type into account is very important in this field of research as Goossens and Buck (2008) indicate soil type as a key factor with respect to dust emission and wind erosion. They also show that ORV driving appears to decrease the threshold on silty surfaces, but increases the deflation threshold in sandy surfaces (Goossens and Buck, 2009).

Goossens and Buck (2009) conclude that the dust produced by ORV activity is one of the main sources of dust around Las Vegas and is a source of environmental- and air pollution. They determined the deflation threshold on different soil types and showed that an increase in vehicle weight results in a higher emission. The relation between the rate of emission and the driving speed was investigated by Etyemezian et al. (2004). They showed that the concentration of sediment increases exponentially with an increase in speed and the emission per vehicle kilometre travelled (vkt) is linear. It should however be noted that the results may be different on dirt roads, as this research took place on paved road. Etyemezian et al. (2003a) and Etyemezian et al. (2003b) show that the emissions per kilometre travelled on a clean road with high speed is comparable to those on a dirty road with lower speed. The dust produced by off-road traffic can exceed the 'background' natural dust, and can even lead to health problems for local people that live along the dirt or off-roads (Nolet and van der Veen, 2009). The actual amount of dust that is produced by off-road vehicles depends in first order on the vehicle speed and mass (Kuhns et al., 2010). Kinetic energy E has a quadratic relation with the speed v and a linear relationship with mass m, given that $E = \frac{1}{2}mv^2$. Increasing speed is expected to result in a –more or less- quadratic increase in produced energy, leading to a quadratic increase in dust emission. The exact relationship depends on for example topography, wind speed and wind direction.

### 2.2 Concentration of suspendable soil particles

The fraction of transported particles that are in suspension in the air have been shown to affect human health (Goossens and Buck, 2014), and is increased in drought conditions (Smoyer-Tomic et al., 2004). The amount of these particles in a unit volume per unit time can be described as the concentration of total suspended particles (TSP) and can be increased as a result of ORV activity (Goossens and Buck, 2011). Particulate Matter (PM) that has a diameter smaller than 10 μm (PM10, fine dust, Dutch: fijnstof) is regarded as air pollution as it is harmful to human health. In addition to PM10, the particulate matter smaller than 2.5 μm is generally used to assess the potential health risks of atmospheric dust. Especially the latter can end up in the lungs and accumulate as the body cannot remove the soil particles by itself (RIVM, 2017; Maas et al., 2015). Goossens and Buck (2014) measured elevated PM10 concentrations up to several hundreds of meters behind an off-road vehicle, even if no dust was visually noticeable. Soil type appears to be an important parameter in the exact concentration levels, as for example the concentrations are higher in silty soils than in sandy soils (Goossens and Buck, 2008). The authors also show that behind the source of emission, concentrations decrease to a safe level after 400 m at driving speeds as low as 24km h-1. At a driving speed of 40 km h-1 the safe distance is 600-800 m. Either staying very far behind a quad, or very close by is recommended, although the latter may be less safe with regard to possible accidents. In-echelon driving is thus strongly dissuaded unless appropriate protection is worn against inhaling the dust (Goossens and Buck, 2008). Using a vehicle based measuring method, the loss of PM10 between the source of emission at an unpaved road and a point 100 m downwind was shown to be less than 9.5%, depending on the roughness of the terrain (Etyemezian et al., 2003b; Etyemezian et al., 2003a). Dust produced from ORV activity can exceed the maximum allowed concentrations as defined in Dutch norms, and can be significantly higher than the background dust that has its origin far away (Nolet and van der Veen, 2009).

## 3. MATERIAL AND METHODS

### 3.1 Area description

Aruba is one of the Leeward islands of the Lesser Antilles and part of the Kingdom of the Netherlands, see figure 1. The climate is semi-arid, almost arid, with a yearly average temperature of 27.5° Celsius and an annual average rainfall of 580 mm. Although the total amount of precipitation is fairly high, the rainfall distribution is seasonal, with high rainfall intensities and a long dry season (Sambeek et al., 2000). The total amount of rain thus falls within a short period of time, resulting in an arid-like climate during the rest of the year. The wind speed and direction are mostly constant throughout the year, with an Eastern trade wind at an average wind speed of 7.7 m $s^{-1}$ (Windfinder, 2017).


**Figure 1: Location of Aruba in the Caribbean Sea.**

### 3.2 Experiment equipment

To measure **dust transport**, the Modified Wilson And Cooke (MWAC) catcher was used. Plastic catchers were placed on a pole at the height of 10, 20, 40, 80 and 160 cm above surface level, assuming that dust would not overtop the highest catcher. The height of the dust cloud was noted in the field, to be able to calculate the total sediment over the full vertical profile of the dust cloud. The resulting values were divided by the inlet area (0.38 $cm^2$) and the total sampling time and the integral efficiency for each of the time intervals to calculate the flux per point in g $cm^{-2}$ $h^{-1}$. More detailed information about the MWAC catcher can be found in Webb et al. (2016), Goossens et al. (2000) and Goossens (2005). Details on the exact construction are in the appendix of supplementary information.

To measure the **dust deposition**, Inverted Frisbee Dust Deposition (IFDD) catchers were used. The IFDD's can be described as the smaller and more low-cost version of the Modified Dust Collector (MDCO) (Sow et al., 2006), although it has the same method of catching sediment. Each Frisbee has a diameter of 24 cm, corresponding to an effective catchment area of 0.045 $m^2$ and is made of iron. In the Frisbee, a sieve is placed with a mesh diameter of 1.3 cm with two layers of marbles on top. These marbles have a diameter of 1.5 cm and serve three main goals: preventing turbulence to occur around the edge of the Frisbees, preventing deposited sediment to be blown away by the wind, and preventing splashing out of the sediment. The IFDD catchers were placed along the road in a transect, and at least one IFDD was placed upwind from the road to analyse the background deposition. For a more detailed description of the catcher, see Goossens and Offer (2000) and Sow et al. (2006). Details on the exact construction are in the supplementary information in the annex.

The vehicle used for the experiments was a Yamaha Grizzly 450 cc. which has a mass of 281 kg weight and is 1.1 m wide and 2.0 m long. This vehicle was chosen as it has the average power of the rental quads in Aruba and is the type of off-road vehicle most used by tourists (Company, 2016).

The wind speed and wind direction were measured in the field using a Davis Vantage Pro 2 weather station. This measurer is used often in field research as it is mobile and easy to transport. The accuracy is fairly high, with ± 3˚ Degree nominal accuracy for the wind direction and the greater of ±2 mph or ±5% deviation for the wind speed (Davis-Instruments, 2011).

The sediment caught was weighed in a Toledo Mettler AJ100 analytical balance, with a readability of 0.0001 g – accuracy unknown.

## 3.3 Standardization of the catchers

In early research on dust transport and deposition, the amount of sediment caught was seen as the actual transport or deposition, and any inaccuracies of the used measurement catcher were not taken into account. However, these raw results taken from the catchers should be standardized in order to arrive at reliable, accurate, absolute values (Sow et al., 2006). Other publications likewise presented the standardization and tried to find the best way of estimating the efficiency factor of the catchers (Goossens et al., 2000; Goossens and Rajot, 2008; Nolet and van der Veen, 2009) or investigators decided to not recalculate the results, but only using them as relative values, only allowing comparison between measured results in a specific situation (Riksen et al., 2016). The standardization is based on the main affecting factors, i.e. wind speed and grain particle size. The wind speed is important as it determines wind pattern, as well as the amount of dust that actually settles on the catchers. For example for the IFDD, the larger the wind speed, the more turbulence will occur over the Frisbee resulting in less sediment being caught by the catcher. The grain size of the sediment caught contains information about the efficiency as each grain size class has its own transport and depositing characteristics (Mendez et al., 2011; Goossens and Offer, 2000; Goossens et al., 2000; Goossens and Rajot, 2008; Goossens, 2005). The absolute efficiency of the measuring devices turned out to be low (Sow et al., 2006), meaning that the errors in the measurements are very large, on the order of hundred percent or more. Furthermore, the efficiency factors vary between different measuring devices. The MWAC for example has fairly high values, ranging between a factor 1 and 0.8, whilst the IFDD shows factors ranging between 0.4 and 0.005 depending on the wind speed. The latter values would mean that an error of more than 200% would be possible when the raw data of research would be used instead of standardizing the values. Standardization of the dust deposition data obtained using the catchers can be difficult, as the actual efficiencies are difficult to estimate and are highly variable (Sow et al., 2006). The MWAC catcher can potentially be used for PM10 and PM2.5 emission studies, although more research is needed to understand and improve the efficiency, as it varies with wind speed and measuring location (Mendez et al., 2016).

Given these arguments, the wind speed and particle size were analysed and used to standardize the results from the research to absolute values of dust transport and deposition. The particle size analyses were performed using a Malvern Mastersizer S laser particle size analyser. For these analyses, a minimum sample weight of a few µg was needed to perform a significant analysis, which was not available in some cases. As a result, average particle size distributions were used to arrive at reliable standardization factors. Figure 2 shows the results of the standardizing factors for the MWAC and IFDD at a variable wind speed. The details of these calculations are given in the appendix.

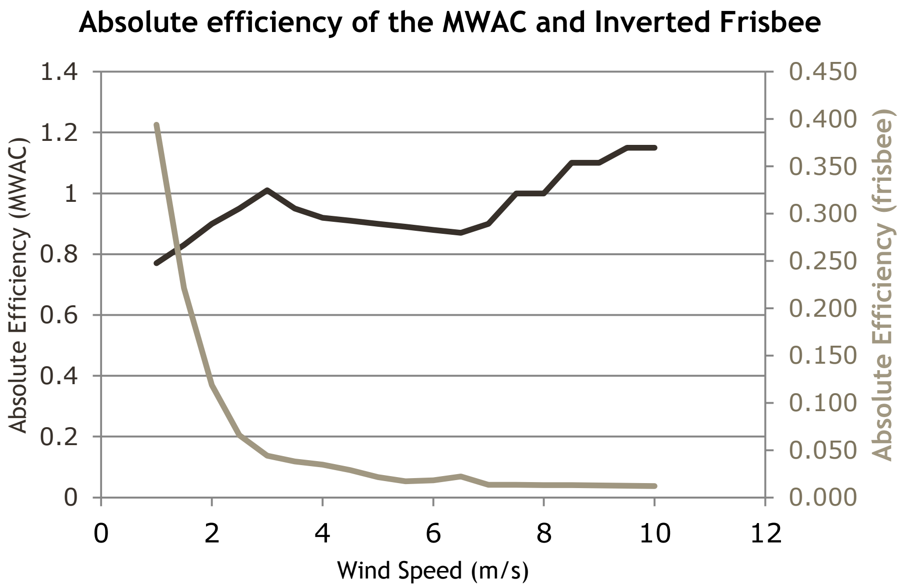


**Figure 2: Absolute efficiency factor of the used catchers for the standardization of the raw data. For the IFDD, the absolute efficiency shows to decrease quickly with an increase in wind speed. The absolute efficiency of the MWAC ranges between 0.8 and 1.2, depending on the wind speed. These standardization values are based on grain size analysis and Goossens and Offer (2000); Goossens et al. (2000) and Sow et al. (2006).**

## 3.4 Dust transport and deposition of period average intensity of traffic

The dust transport and deposition of ORV traffic was analysed to find out how much sediment was transported at an average level of traffic, and to find out the spatial deposition pattern of the dust. The reference level of 90 off-road vehicles per hour was taken, which is within the range (50 min./140 max.) of the traffic density on the off-road and dirt roads along the Northern coast. Data were collected during a field day in the Northern area of Aruba, where an existing off-road track was chosen along the Northern Coast on the road from Bushiribana (Gold smelter ruins) to the Natural Bridge (12°32'51.1"N 69°58'00.1"W, figure 3). The road is perpendicular to the prevailing wind direction which allows to assess the spatial deposition pattern of the dust. Two MWAC poles were set up at a distance of 1 metre downwind of the road. In addition, a transect of IFDD's was placed along the road, at 6.25, 12.5, 25, 50, 100, 200 and 300 m downwind, as well as two background measurers 20 m upwind from the road to assess the background deposition at the time of the experiment. All catchers were installed for three hours in a row, from 9 a.m. to 12 p.m. The wind vane of the Davis Vantage Pro 2 weather station was installed at 1 m above surface level and the wind speed and wind direction were noted every 15 minutes after Goossens (2016) and Bosveld (2016).

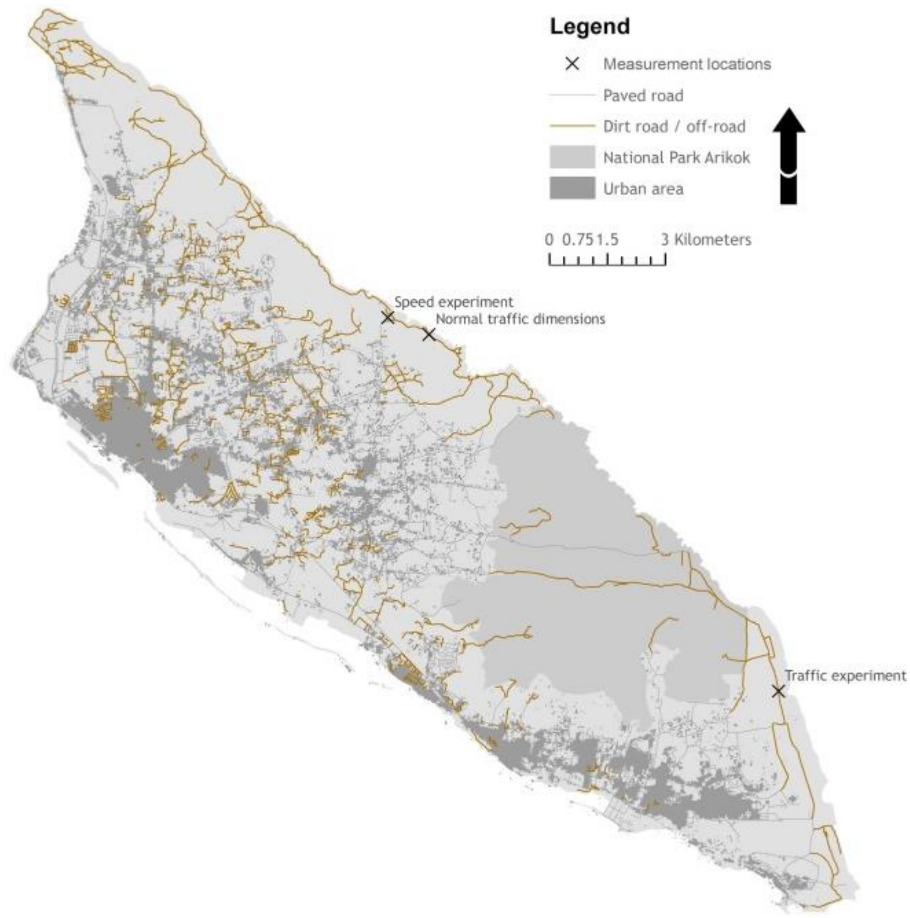


**Figure 3: The island Aruba with all the paved and unpaved roads shown together with the urban areas and National Park Arikok as a reference. The measurement locations are situated along the North-eastern coast and are marked with a grey cross.**

## 3.5 Determining the effect of different traffic densities

The effect of different traffic densities was assessed by performing an experiment with a quad as an example of an off-road vehicle. The selected location is just inside the shooting terrain of the Ministry of Defence of the Kingdom of the Netherlands (12°27'48.5"N; 69°53'02.3"W, figure 3). This is a quiet area, the vegetation cover is low and the topography and soil type is representative for the Northern coast area where most of the dirt and off-road driving takes place. Within the site, 6 plots of each 30 metres long and 3 metres wide were prepared. On the plots, we drove with different densities of 40 (3 replications) and 80 times (3 replications). The plots were installed side by side with the longest axis in the prevailing wind direction so that the dust produced at one plot did not end up in the next plot but was taken outside the test site by the wind. This had the drawback that absolute values of dust transport and deposition could not be calculated from the experiments, as the sediment caught was emitted from the full length of the plot: the IFDD located at 10 metres downwind from the plot is situated at 40 metres from the upwind end of the plot, meaning that a spatial distribution pattern could not be determined. On each plot, the quad used the same track every time, to allow to assess the difference in impact on dust transport and deposition between the traffic densities.

Figure 4 shows the experimental setup. Dust transport was measured at 5 m downwind from the plot. Because of the limited amount of MWAC catchers available, measurements were done without replications: one measurement for a plot with 40 passes and one for 80 passes. The five samplers were placed on the standard heights of 10, 20, 40, 80 and 160 cm.

The deposition pattern was analysed by placing IFDD catchers at a distance of 10, 25, 50, 100 and 150 m downwind from the downwind end of the plot. Two extra catchers were placed at 50 m, 5 metres left and right from the catcher in the transect, to assess potential errors in the measurements as a result of a short term deviation in the wind direction. In addition, three catchers were placed upwind from the experimental site to investigate the background deposition rate, which was subtracted from the amount of sediment caught in the other catchers.

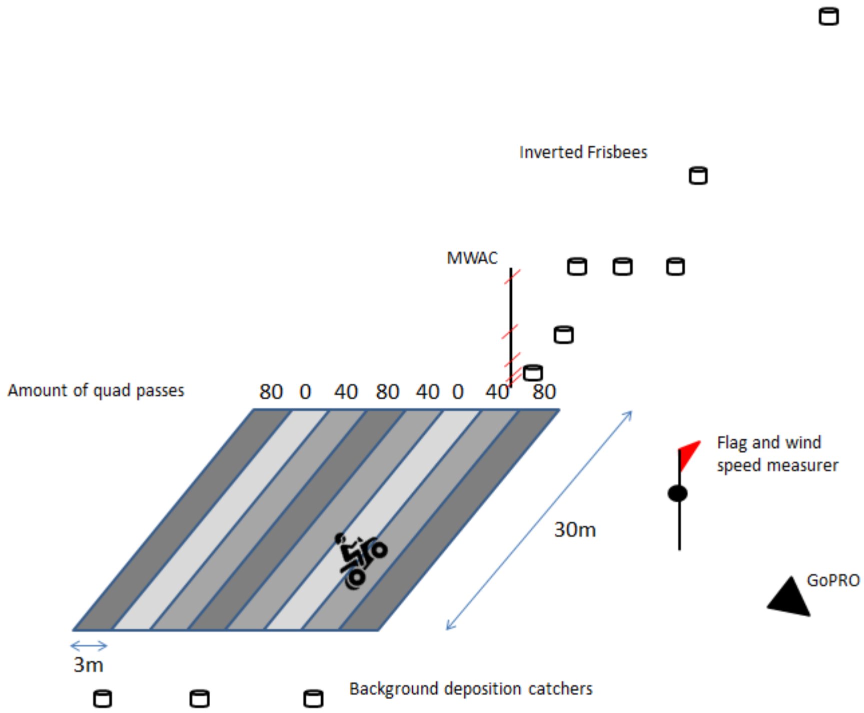


**Figure 4: Setup of the experiment to assess the impact of an increase in traffic density on the dust transport and deposition flux with ORV activity. The wind direction is indicated with the red flag, and two Modified Wilson And Cooke (MWAC) catchers are drawn, together with 7 Inverted Frisbee Dust Deposition (IFDD) samplers in a transect downwind and three IFDD's upwind from the plots.**

Each plot was treated for 30 minutes, and after each test, the catchers were emptied and moved to the next plot. The same amount of time per plot was used to measure the actual effects of a certain amount of passes per time unit. The actual wind speed was measured every minute during the treatment of the plots and the wind direction was defined by placing and filming a flag, to see eventual wind direction changes.

## 3.6 Determining the effect of different driving speeds

The effect of different driving speeds on the dust transport and deposition flux was investigated using a quad driving at three speeds, i.e. 10, 25 and 45 kmph, on an existing off-road track along the Northern coast. Time limits constrained the experiment, therefore three speeds were chosen as it is the minimum allowing to check results for non-linearity. The highest driving speed (45 kmph) is the maximum driving speed that is safe and possible on the off-road tracks. During each speed test, one track was driven 60 times. The length of the driving tracks was about 40 m, so that the turning points were far enough to not affect the sediment caught in the catchers.

In figure 5, the experimental setup is shown. The chosen location is on a track leading from the gold smelter ruins to the natural bridge (12°33'04.1"N; 69°58'33.0"W, see figure 3) where off-road driving occurs and most tourist routes pass. The experiment took place in the morning, when the traffic density is lower than average, so that the experiment was not affected by the background traffic. The catchers were covered whenever a vehicle, other than the quad for the experiment, passed.

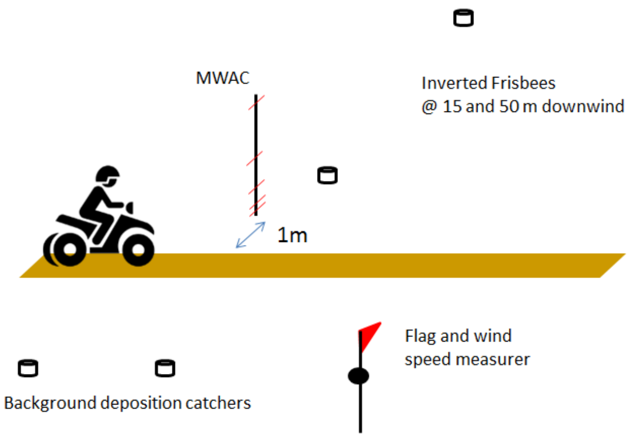


**Figure 5: Setup of the speed experiment to assess the impact of different driving speeds on the dust transport and deposition flux with ORV activity. The quad drove over one track 60 times at three different driving speeds (10, 25 and 45 kmph), passing one Modified Wilson And Cooke catcher and two Inverted Frisbee Dust Deposition (IFDD) samplers.**

For each of the speed tests, one MWAC pole was placed with five samplers on the standard heights above surface level. The pole was placed at the exact same location, at about 1 m downwind from the track where the quad passed. In addition, two IFDD catchers were installed at 15 and 50 metres. These distances are far enough to prevent small scale erosion processes to end up in the catcher, but close enough to catch an amount of sediment that is still well-measurable so that a comparison was possible between the three speed tests. Lastly, two IFDD catchers were installed upwind to assess the background deposition to be subtracted from the caught values from the experiment.

## 3.7 Assessing the concentration of suspendable soil particles

To assess the potential health impact of the ORV activity in Aruba, the data gathered in the experiments were analysed using the formula from Nolet and van der Veen (2009): $C = \frac{G*(10^6)}{S*t*u}$ in which C is the average concentration of sediment in the transport in µg $m^{-3}$, G the sediment caught with the MWAC in kg, S the catching area in $m^2$, t the total sampling time in seconds and u the measured average wind speed within the time interval of the measurement in m $s^{-1}$.The concentrations were defined in total suspended particles (TSP), PM10 and PM2.5 as being the most important parameters for assessing health risks of dust. This was done by dividing the calculated concentrations by the percentage PM10 and PM2.5 in the sediment caught that was analysed on grain size diameter. As found in the theory, the efficiency factor for measuring concentration rates using the MWAC remains unknown. For the recalculations in this research, the same efficiency factor was used as for the dust transport.

# 4. RESULTS

## 4.1 Dust cloud dimensions of period average intensity off-road traffic

The extent of off-road driving in Aruba varies from time to time and place to place. The approach was chosen to select and analyse the traffic at a representative location in terms of traffic density and composition of the road material. The integral efficiency for the dust deposition was 0.903 (-). Figure 6 shows the total amount of dust transported by the average traffic after the measuring time of 3 hours. As the dust just rose over the top of the MWAC in the field (at 200 cm), the integral of the fitted function was calculated for 0>x<200, resulting in a total dust transport flux of **9.24 g cm$^{-2}$ h$^{-1}$** over the full vertical profile of the dust cloud, or 924.3 g m$^{-2}$ h$^{-1}$.

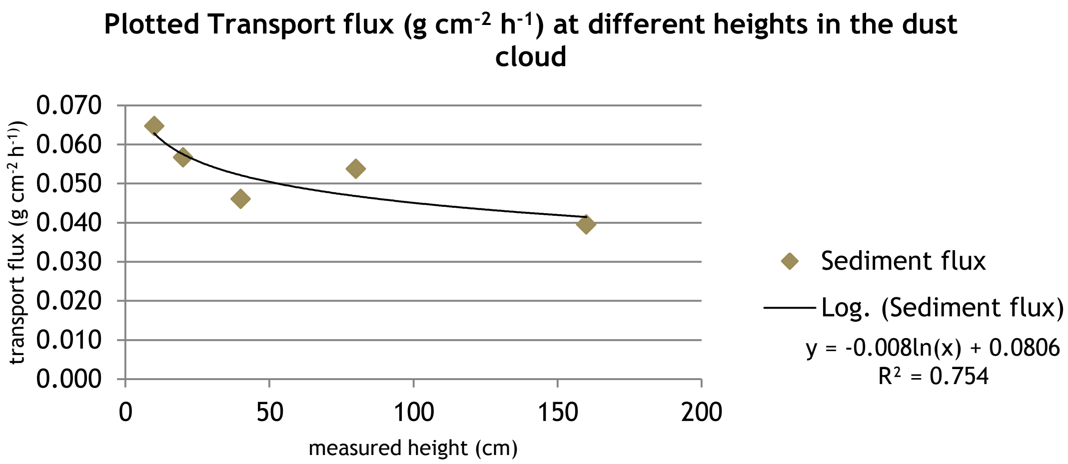


**Figure 6: Measured transport flux at different heights of the dust cloud plotted in a graph. A logarithmic trend line is drawn which shows a decrease in transport flux over the vertical profile. Calculating the area below the graph for 0>x<200 yields the total transport flux of 9.24 g m$^{-2}$ h$^{-1}$.**

The spatial deposition pattern of the dust was analysed by dividing the value of sediment caught by the catchment area of the IFDD (0.045 m$^2$), the total sampling time (3 hours) and the integral efficiency for the 20 time intervals (0.0241) to yield the deposition flux in g m$^{-2}$ h$^{-1}$. Next, the average background deposition (6.12 g m$^{-2}$ h$^{-1}$) was subtracted from the resulting value to result in an increased deposition flux. In figure 7, the net spatial dust deposition is shown as a function of distance from the source. The fitted curve quite closely approximates a hyperbola, as the exponent of the power function is close to -1.

The flux as measured with the IFDD's shows a steep decrease in the dust deposition flux with distance to the source, but shows nearly constant levels starting from 200 m. Integrating the fitted function, the total deposited sediment in the transect 10-300 metre is 1237 g m$^{-1}$ h$^{-1}$. Even though the flux has strongly decreased at a distance of 200 m from the source, the rates are still higher than the background deposition rates.

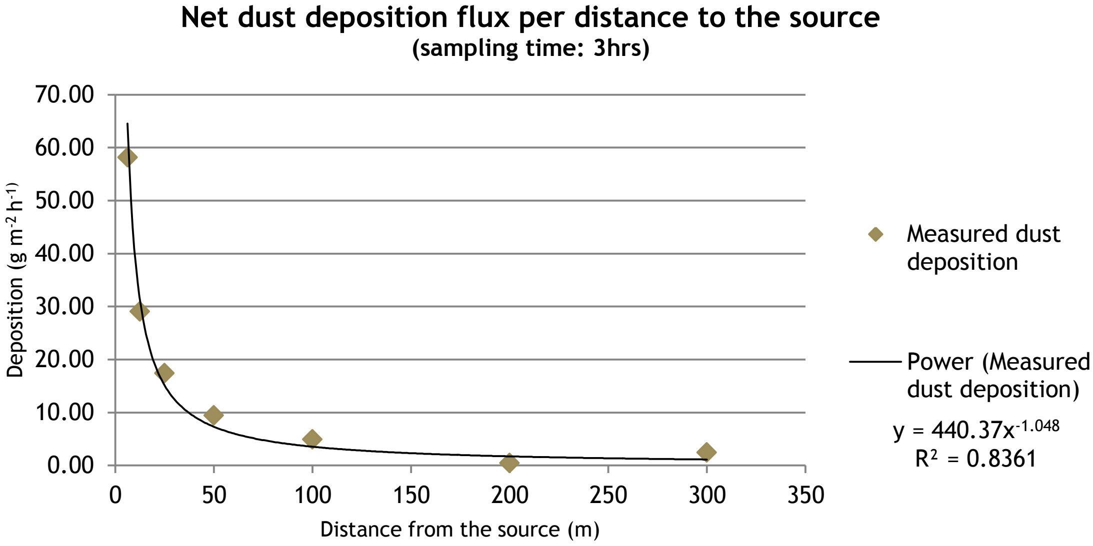


**Figure 7: The net dust deposition flux per distance to the source as a result of the measurements along the off-road track with period average level of traffic. Net means that the background deposition rate has been subtracted from the measured rates in the downwind IF's. The function shows a steep decrease per distance from the source and a slow decrease from 200 m from the source onwards.**

## 4.2 Effect of different traffic densities

The transport fluxes for the different passing densities were measured in plot 1 and 2 of the traffic density experiment. The total area below the curves (10-170 cm height) in figure 8 yields the total transport flux for the vertical profile of the dust cloud: 13.18 g for plot 1 and 5.06 g for plot 2, meaning that by doubling the traffic density, the transport flux increases with factor 2.61.

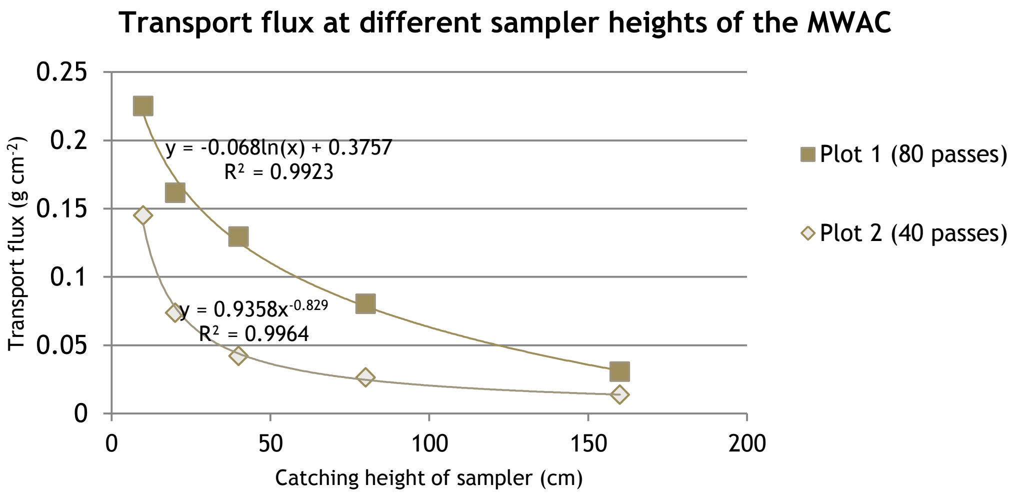


**Figure 8: The transport flux at different sampler heights of the MWAC of period average traffic on the off-road track. The integral of the functions yields the total dust transport for the full vertical profile of the dust cloud and is 13.18 g for 80 passes and 5.06 g for 40 passes. This means that doubling the traffic density results in an increase in dust transport with a factor 2.61.**

In table 1, the average rates of deposition at the various distances from the source are shown, as well as the standard deviation of the average numbers. The high standard deviations can be due to the difference in driving style of the drivers, the varying degree of vegetation cover on the plots and the texture differences between each plot. The increase factor is higher than 1 for each catchers, except for the catcher at 100 m.

The catcher at 10 m is the only catcher where more dust per pass was deposited, as 3 times more sediment was caught during the 80 passes compared to the 40 passes. This means that 1.5 times more deposition occurred per pass.

Figure 9 shows the net deposition flux at 0-150 metres distance from the plots in the experiment. Before standardizing the results, the average background deposition of 0.20 g $m^{-2}$ $h^{-1}$ was subtracted. Integration of the function between x=10 and x=150 yields the total net deposition flux on the horizontal profile between 10 and 150 metres from the source and is 24.17 kg $m^{-2}$ and 37.21 kg $m^{-2}$ for 40 and 80 passes respectively. The values below x=10 were not taken into account because the form of the curve is unknown for the area 0<x<10. It should be noted that the results are in kilograms in total, so not per pass or per unit driven length. The results show an increase in deposition flux over the area 10-150 metres with factor 1.54 when doubling the traffic density from 40 to 80 passes. This means that a lower deposition flux per pass occurs when increasing the passing density.

**Table 1: The average net standardized deposition rates per distance from the source for the two passing densities 40 and 80 from the experiment. The standard deviation (SD) of the three replications is shown, as well as the increase factor per distance.**

| Distance (m) | 40 passes | | 80 passes | | Increase factor |
|---|---|---|---|---|---|
| | Average | SD | Average | SD | |
| **10** | 915.8 | 216.3 | 2729.3 | 1316.8 | 3.0 |
| **25** | 387.8 | 107.9 | 453.7 | 271.0 | 1.2 |
| **50** | 124.9 | 10.4 | 173.9 | 44.9 | 1.4 |
| **100** | 119.6 | 45.9 | 111.7 | 56.2 | 0.9 |
| **150** | 57.7 | 28.3 | 76.6 | 21.1 | 1.3 |

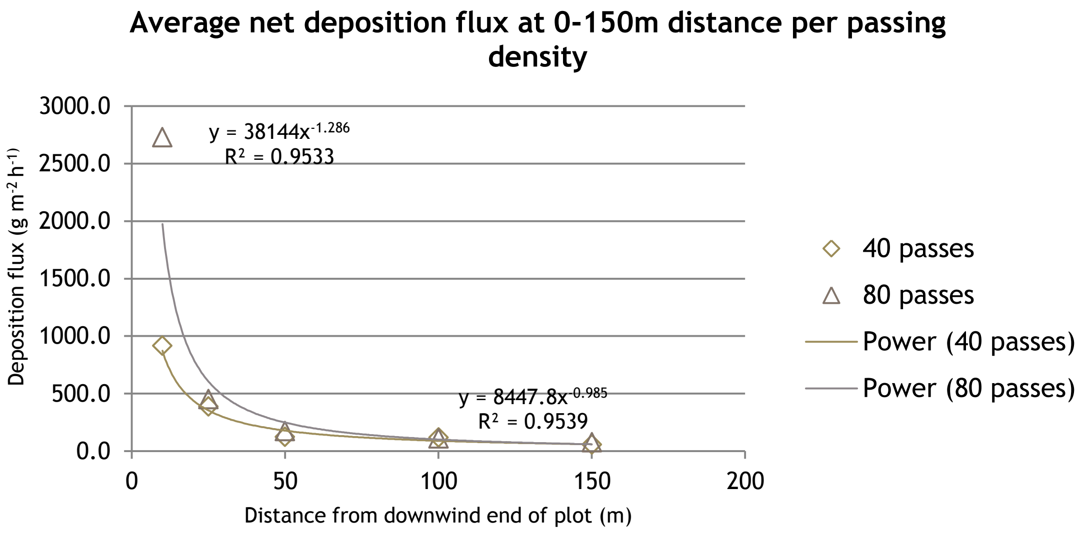


**Figure 9: Average net deposition flux at 0-150 m distance downwind from the plots, based on the three replications per passing density.**

## 4.3 Effect of different driving speeds on dust transport and deposition

Figure 10 shows the effect of different driving speeds on the dust transport. The quad passed the catchers 60 times at each driving speed, i.e. 10, 25, 45 kmph. The integral of these functions was calculated and yields the total dust transport ($cm^{-1}$) per driving speed. Table 2 shows these results of the total transport flux ($cm^{-1}$) per pass per driving speed, and the transport flux per vehicle kilometre travelled (vkt) in grams.

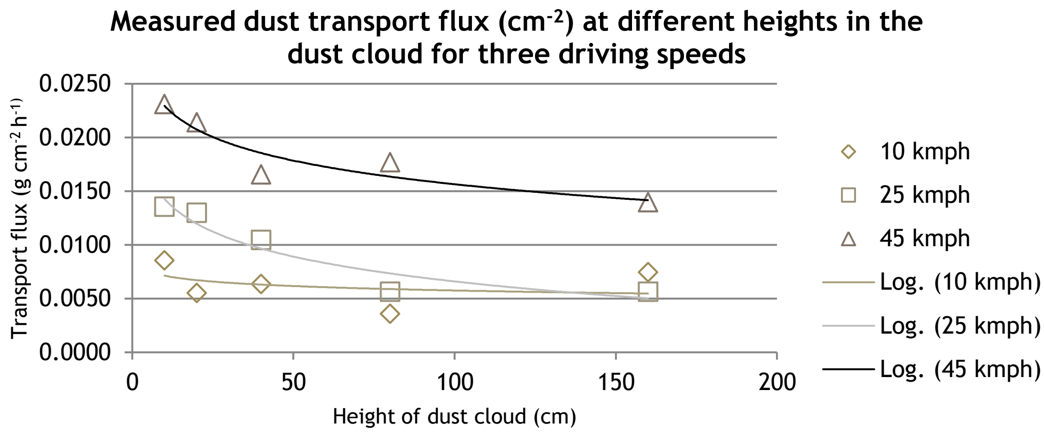


Figure 10: The effect of driving speed on the dust transport flux as measured in the experiment. A clear increase in dust transport can be observed per driving speed. The sediment caught decreases with the height of the dust cloud. As the visible dust cloud just rose over the MWAC pole, it was assumed that transport only took place between 0 and 170 cm height above surface level. Integration of the functions then yields 1.02, 1.63 and 3.04 g $cm^{-1}$ transport per 60 passes for the driving speeds of 10, 25 and 45 kmph respectively.

Table 2: The total transport flux ($cm^{-1}$) (per pass) per driving speed and the total transport flux per vehicle kilometre travelled (vkt) in grams.

| Speed (kmph) | Total flux (g $cm^{-1}$) | Total flux (g $m^{-1}$) | Flux per pass (g $m^{-1}$) | Transport flux per vkt (g) |
|---|---|---|---|---|
| **10** | 1.02 | 102.32 | 1.71 | 1705 |
| **25** | 1.63 | 163.07 | 2.72 | 2718 |
| **45** | 3.04 | 304.17 | 5.07 | 5070 |

The effect of a speed increase on the dust deposition was measured with IFDD catchers at 15 and 50 metres. As the other rates measured with IFDD's in the research show a logarithmic decrease of dust deposition with an increasing distance, a logarithmic trend line was drawn in the graph between 15 and 50 m distance from the source. Integration of these functions for 15>x<50 yields the values as shown in table 3, of which the background deposition of 1.89 g $m^{-2}$ $h^{-1}$ was subtracted from the results. The increase in driving speed shows an increase in dust deposition per $m^1$ per pass, i.e. 3.55 g at 10 kmph, 5.74 g at 25 kmph and 7.74 g at 45 kmph.

Table 3: The effect of driving speed on the total deposition flux between 15-50 m in the experiment and per pass.

| Speed (kmph) | Total deposition flux between 15-50m (g $m^{-1}$) | Per pass (g $m^{-1}$) |
|---|---|---|
| **10** | 212.87 | 3.55 |
| **25** | 344.17 | 5.74 |
| **45** | 464.36 | 7.74 |

## 4.4 Assessing the concentration of suspendable soil particles

As a start of assessing the potential health risks from off-road driving, the concentration of total suspendable particles (TSP), PM10 and PM2.5 was calculated from the results from the MWAC measurers. Table 4 shows the resulting concentrations related to the maximum norm concentrations that are allowed in the Netherlands.

Table 4: Overview of the norms of maximum day and year average of TSP, PM10 and PM2.5 in the air in the Netherlands (RIVM, 2017).

| Fraction: | Maximum day average | Maximum year average |
|---|---|---|
| **Total Suspended Particles (TSP)** | 150 µg $m^{-3}$ | - |
| **PM10** | 50 µg $m^{-3}$ (max. 35 days exceeded) | 40 µg $m^{-3}$ |
| **PM2.5** | 35 µg $m^{-3}$ | 25 µg $m^{-3}$ |

The concentration along the road was calculated for the full vertical profile column of the MWAC measurer ($0.02m^2$), where 0.00924 kg of dust passed in 3600 seconds with an average wind speed of 4 m $s^{-1}$. The average concentration TSP is then 32.08 µg $m^{-3}$, which is lower than the allowed maximum norms. The impact of different driving speeds on the concentrations of TSP, PM10 and PM2.5 was assessed for the full vertical profile column of the MWAC measurer ($0.018m^2$). The concentrations of PM10 and PM2.5 were calculated by dividing the TSP concentrations by the percentage PM10 and PM2.5 in the sediment caught, i.e. 4.6% and 2.6% respectively. These rates were taken from the particle size analysis. Table 5 shows the measured concentrations during a pass at the three driving speeds of 10, 25 and 45 kmph. The results show high levels of PM10 and PM2.5, exceeding the maximum allowed norms at a driving speed of 25 and 45 kmph directly along the road and based on the wind speed ranging between 3.6 and 4.2 m $s^{-1}$. Table 6 shows however that the **average** concentrations –including the time of turning and approaching with the quad- do not exceed the maximum norms when analysing the rates during the full experiment.

**Table 5: Calculated concentrations in TSP, PM10 and PM2.5 per pass at the three driving speed levels of 10, 25 and 45 kmph.**

| Speed (kmph) | TSP | PM10 (4.6%) | PM2.5 (2.6%) |
|---|---|---|---|
| 10 | 526.3 µg $m^{-3}$ | 24 µg $m^{-3}$ | 13.8 µg $m^{-3}$ |
| 25 | 943.7 µg $m^{-3}$ | 43 µg $m^{-3}$ | 24.8 µg $m^{-3}$ |
| 45 | 2235.3 µg $m^{-3}$ | 102 µg $m^{-3}$ | 58.8 µg $m^{-3}$ |

**Table 6: Average concentrations in TSP, PM10 and PM2.5 during the experiment at the three driving speed levels of 10, 25 and 45 kmph. Average means throughout the entire experiment, including the turning and approaching of the quad.**

| Speed (kmph) | TSP | PM10 (4.6%) | PM2.5 (2.6%) |
|---|---|---|---|
| 10 | 13.2 µg $m^{-3}$ | 0.6 µg $m^{-3}$ | 0.3 µg $m^{-3}$ |
| 25 | 18.9 µg $m^{-3}$ | 0.9 µg $m^{-3}$ | 0.5 µg $m^{-3}$ |
| 45 | 33.5 µg $m^{-3}$ | 1.5 µg $m^{-3}$ | 0.9 µg $m^{-3}$ |

## 5. DISCUSSION AND FUTURE RESEARCH

### 5.1 Comparing the results with the expectations from literature

The effect of off-road driving on the production of dust was expected to be present as indicated by Goossens and Buck (2009) and Nolet and van der Veen (2009) and indeed exceeded the background deposition rates up to at least 300 m from the road. The increase of the dust transport and deposition with an increase in speed was expected to occur (Etyemezian et al., 2004) and the results from the driving speed experiment confirmed these expectations. The effect of an increase in traffic density on the dust cloud dimensions was not yet known, except for the knowledge from Kutiel et al. (2000) and Nortjé et al. (2012) who showed that most soil compaction occurs after the first few passes. The relation between traffic density and dust transport appears to be more or less exponential, whereas the total net dust deposition decreases per pass increase. The latter indeed shows that the first passes affect the emission rates most, which could be caused by less sediment that becomes available to be transported as off-road driving causes progressive coarsening of the soil top-layer (Goossens and Buck, 2008). The results however show a high standard deviation, meaning that more replications would have been needed. The impact of off-road driving on the soil compaction and soil water erosion was shown by for example Buckley (2004) and, as expected, clear signs of water erosion on the tracks were observed after the traffic density experiment. In addition, the tracks appeared to serve as waterways after rain storms, as can be seen in the pictures in the supplementary annex. The effect of quad driving on compaction, and the subsequent effects on water erosion and availability of sediment for wind erosion remains unknown. Off-road driving was expected to increase the concentration of PM10 and PM2.5 levels (Goossens and Buck, 2014) and in addition, a negative effect on the concentration of the driving speed was expected (Goossens and Buck, 2011). Given the results from for example Goossens and Buck (2014), the health of people can be potentially at risk as a result of off-road vehicular activities. The results from the calculations of the concentrations TSP, PM10 and PM2.5 in the speed experiments show that the Dutch norms are likely to be exceeded under certain conditions. The actual concentration rates for the various off-road vehicles are however still not known. Although most urban areas along the Northern coast are situated alongside or near dirt or off-road tracks, the concentration of dust more distant from the source is not yet assessed. Reconsidering this in future research could give more insight in the spatiotemporal variation in concentration rates of fine dust.

### 5.2 Restrictions in extrapolating the results

Due to time constraints, the experiments in the research could only take place for a short period of time, thus not allowing to take the climate during the rest of the year into account. In addition, the measurement period was relatively wet compared to the average climate conditions, and the wind speeds were lower than normal. During the measurement period between November and December, the weather conditions could have resulted in lower rates than normally because of three reasons: First, this measuring period fell just outside the high season for tourists so less traffic was present. Secondly, the relatively wet top soil resulted in less dust production and thirdly, the wet soils resulted in the presence of ponds and small gullies on the dirt roads, which had an effect on the driving speed of the off-road vehicles. Because of this, the results could be significantly higher in dry times than the results presented here. The importance of taking into account the drought conditions can be also stressed as in these periods the potential health risk for the local people can be highest (Smoyer-Tomic et al., 2004; Goossens and Buck, 2014).

More information is still needed in order to get a clearer picture of the actual dust cloud dimensions. Extrapolating the results will not be immediately possible, because actual dust transport and deposition and concentration rates depend on various time and location specific conditions such as soil type, topography, wind direction, vehicle type, road conditions and weather, of which the latter has been discussed already. Firstly, soil type plays a role as the texture of the soil influences the rate of emission (Goossens and Buck, 2014). The results from this research apply for soil types along the Northern coast (local name: Tonaliet). However, large differences in dust cloud dimensions may occur on other parts of the island, where the soil is likely to be less coarse. Secondly, topography influences the actual dust transport and deposition rates, as for example walls or vegetation can prevent the dust from flying far inland. Thirdly, the wind direction and speed determine the dimensions of the dust as well as the potential health risk. The results from this research are based on the wind speed that was present during the measurements. Given the wind speed was already lower than usual in Aruba as has been discussed, this also means that there are no results available for other wind speeds. What would happen to the dust cloud dimensions if the wind speed would increase, remains unknown. Depending on the soil texture, more sediment could become available for erosion, but the dust concentration could also decrease as the flux per time unit decreases. The road conditions can affect the average driving speed of vehicles and thus affect the dust being produced. Lastly, the vehicle type influences the dust cloud dimensions, which has not been taken into account. The results from the experiments are based on the dust production of a quad and do not refer to cars or trucks or other vehicles, which produce significantly more dust because of their larger mass (Goossens and Buck, 2008; Kuhns et al., 2010) and could thus also increase the concentration rates of TSP, PM10 and PM2.5.

## 5.3 Deviations as a result of chosen material and methods

The importance of standardizing the raw dust transport and deposition data was expected to be important as stressed by for example Goossens et al. (2000). Based on the particle size distribution and wind speed, the standardization factors were defined using the formulas provided by Sow et al. (2006) and were shown to be low as expected, especially for the IFDD catchers. The design for using the catchers in the field should be considered carefully as they are sensitive to micro topography and wind turbulence. Every small shrub can already cause differences in results. Standardizing the results from the field is therefore again shown to be difficult, yet very important. The relative results in the research are characterized by a high $R^2$, reflecting the expectations from literature and the observations in the field. Extrapolating the data to monthly and absolute rates however is still difficult, especially because the measuring periods in the research were short – with a maximum of three hours. The IFDD catchers appear to be less efficient at high wind speeds. This is a strange characteristic, as one would expect devices to measure wind erosion to be efficient when wind is present. The reason for choosing the IFDD catchers was the initial focus of the research on long term measurements. The marbles were included in the final design as they slightly increase the efficiency (Sow et al., 2006).

The results in grain size analysis that led to the efficiency factors for the standardization of the data were based on the average size distribution of the sediment caught. The particle size distribution can however vary between the different MWAC and IFDD catchers, as for example the particle side distribution of sediment caught in the IFDD at 10 metres was different from the one at 50 metre distance. However, analysing them all would be too costly, and in most cases, the sediment available was not sufficient to execute the particle size analysis. Definitely, more research is needed to find out the particle size distribution over the transect, as during the data collection not enough sediment was caught to be analysed. Grain size was assumed not to vary in the different soils on the different measurement locations, as the soil type was assumed to be identical. This was however not experimentally established, but based on soil data from maps and observations. Finally, the standardization of the MWAC for measuring the concentration rates was assumed to be identical to the standardization for the dust transport calculations, which has not been analysed prior to the research.

For this research, the MWAC was selected as it was cheaper and easier to construct. The drawback was that measuring the background transport flux during the measurements was not possible because of the low amount of sediment available, meaning that the resulting transport rates always include the background transport flux. In addition, the sediment inlet of the MWAC is relatively small. As the measurements were executed in a short time period, the sediment caught was limited in some cases which was a drawback of the chosen catcher.

The two extra IFDD catchers at 50 metres in the traffic density experiment that were placed to assess an eventual deviation in the wind direction did not lead to a need of recalculating the results. The passing dust cloud at this distance appeared to be as broad as 10 metres meaning that the sediment caught was more or less equally over the three catchers at that specific distance from the source. No catcher showed higher rates than the IFDD in the transect, meaning that the dust cloud did pass over the transect, which was also observed in the field. In addition, the wind direction during the measurements turned out to be very constant, resulting in dust clouds passing all IFDD catchers along the transect.

## 5.4 Relevance of the results for Aruba

On the map in figure 11, the dirt roads in the Northern part of Aruba are shown. In addition, the average wind direction is given, showing the predominant Eastern wind that can blow the dust over the island from the dirt roads along the Northern coast. The results show that the dust can be carried up to at least 300 m inland meaning that a significant part of the urban areas is prone to dust from off-road driving. The highest risk is estimated to occur in the urban areas, and the regions where dirt roads are located in between the houses, as for example Ayo, where high traffic densities are present. Lastly, in these regions the soil type is likely to be less coarse thus more susceptible to be detached by vehicular activity.

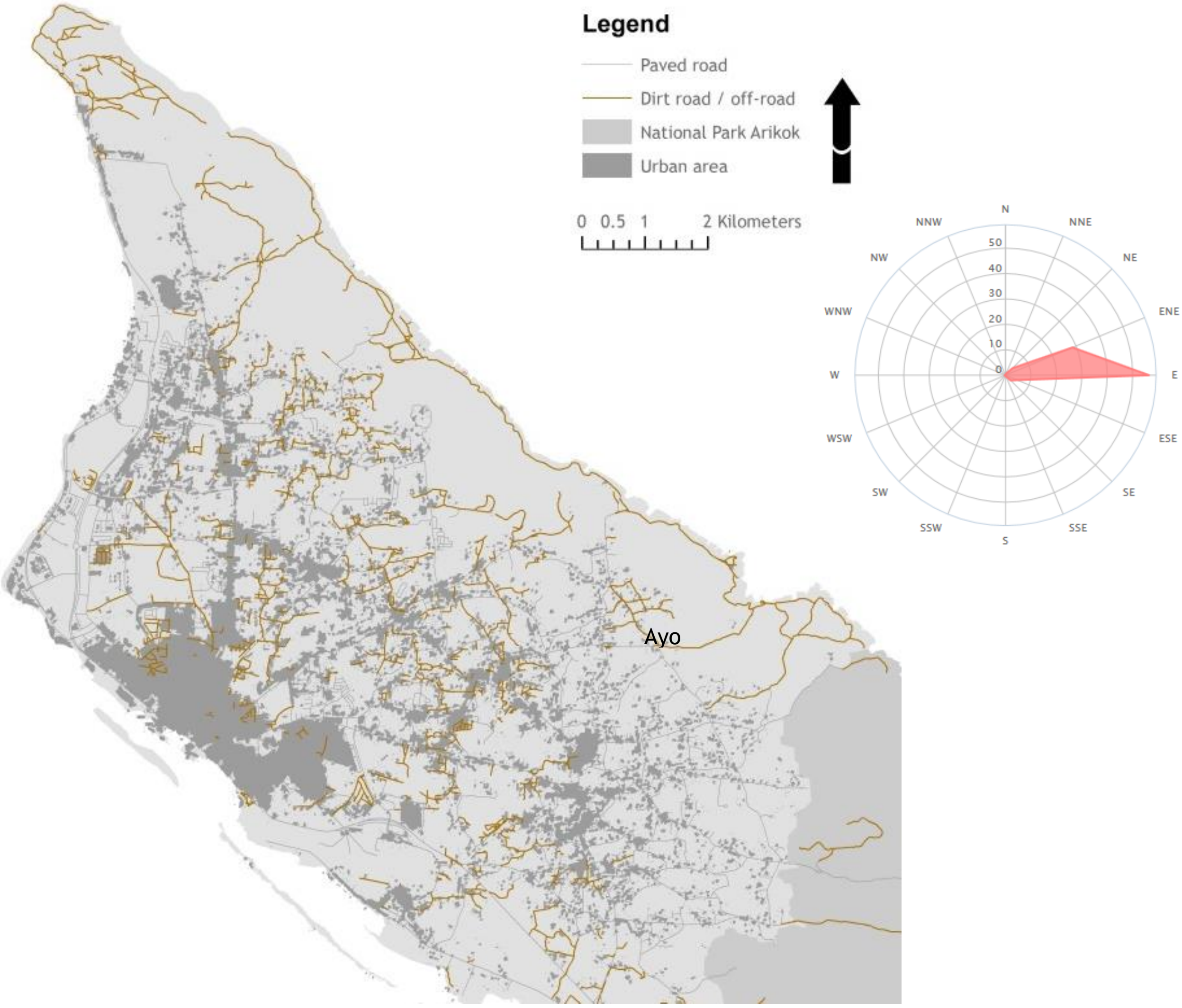


**Figure 11: The Northern part of Aruba, showing several kilometres of dirt roads. The wind is predominantly blowing from East and can take the dust produced along the Northern coast over the island, up to the regions where urban areas are situated. Wind rose retrieved from Windfinder (2017).**

## 6. CONCLUSIONS

To our best knowledge, the dust transport and deposition caused by dirt- and off-road driving in Aruba has not been assessed prior to this research. In this research, the dust cloud dimensions have been assessed to bridge this knowledge gap by measuring both the dust transport and deposition spatial pattern from period average intensity of traffic. In addition, experiments helped to learn more about the effect of different driving speeds and traffic densities on the dust cloud dimensions. As a result, five conclusions can be drawn.

Firstly, the dust cloud dimensions produced by average intensity off-road traffic in Aruba are shown to decrease rapidly with distance from the source, but remain more or less constant from 200 m onwards, meaning that the dust produced by off-road vehicles along the Northern coast is likely to reach far inland.

Secondly, the dust deposition flux was shown to increase when traffic density increased, especially close to the source, although the results varied between the different drivers and the standard deviation was high. The total deposition flux over the full transect decreased per pass throughout the experiment, possibly as a result of a decrease in available sediment material. The dust transport increased almost exponentially, with the transport flux for 80 quad passes 2.61 times higher compared to 40 quad passes.

Thirdly, a clear negative effect of increasing the driving speed on the dust transport and deposition was shown, where the dust transport increased exponentially when the driving speed increased: 1.71, 2.72 and 5.07 g $m^{-1}$ per pass for 10, 25 and 45 kmph respectively. The dust deposition increased more than linear: 3.55, 5.74, 7.74 g $m^{-1}$ per pass between 15 and 50 m from the source for 10, 25 and 45 kmph respectively.

Fourthly, the concentration of both PM10 and PM2.5 appeared not to exceed the allowed norms for the average intensity off-road traffic along the Northern coast. However, the concentrations measured during the driving speed experiment are surprisingly high and did exceed the maximum allowed norms, which is most probably undesirable with regard to human health. The high concentrations can have an effect as the prevailing wind direction in Aruba is East with an average wind speed of 7.7 m $s^{-1}$, blowing the dust from the dirt- and off-road traffic over the urban areas around Bushiribana, and maybe even up to Noord and Oranjestad.

Lastly, the results from this research are time and location specific and dust cloud dimensions produced by ORV traffic strongly depend on which type of **vehicle** is driving with what **speed** over what type of **surface** during which **weather** conditions. The measured results in the experiments are likely to be higher in the case of heavier off-road vehicles, and further detailed research is needed to create a better understanding on this matter.

## 7. RECOMMENDATIONS

Raising the awareness of off-road drivers for caring about the environment is important and a more strict guidance through sustainable management is recommended. The results show the effect of an increased speed on the extent of dust transport and deposition dynamics and therefore, reducing the speed when driving on dirt roads is recommended. This should be enforced by the government, and stressed by for example tour operators as they are key stakeholders for raising the awareness of tourists and are currently not taking into account the environmental issues.

Standardizing the raw results from the catchers again appeared to be very important to arrive at realistic absolute dust transport and deposition fluxes. The efficiency factors of the catchers therefore are very important, but remain empirical. In depth research could help to get a better understanding of the efficiencies per catcher with different wind speeds and soil textures, more in particular for the dust cloud dimensions produced by off-road vehicles.

With regard to the dust concentration rates, keeping an eye on the effects on human health of off-road and dirt road driving is recommended. These effects and recommendations are important for the off-road drivers, yet maybe even more important for the local people that live close by the dirt roads and face high concentrations every day. More detailed research should investigate the actual concentration rates further from the road, and the variation in concentration rates between various off-road vehicles. The discussion shows that the measured rates are likely to be higher for vehicles with a larger mass, which emphasizes that restricting heavy vehicles as trucks and buses from the dirt roads should be considered.

# 8. ACKNOWLEDGEMENTS

I am grateful to Klaas Metselaar and Michel Riksen for their support with setting up and executing the research. Their comments and suggestions have materially improved this paper. Klaas, thank you for being my supervisor from the very start and encouraging me to take one step extra each time. I am very grateful for the support from Emil ter Horst in Aruba. Thank you for arranging all the transport and accommodation and introducing me to the *amazing days* in Aruba. Anouk Horn and Siebe Houtsma who assisted with field work. I also acknowledge guidance from Dirk Goossens, for his positive feedback and help with analysing the samples. Vic Etyemezian for his support and introducing me to this field of research. The ministry of Defence located in Savaneta and their willingness to allow access to the shooting terrain at Vader Piet. I am grateful to Wageningen University in general and its employees who educated, developed and assisted me in the first steps into the world of science. Finally, I want to thank my wife Christine for joining me to the Caribbean. We have been blessed with loving people and great experiences on the different islands and we both know none of this was possible without our Father. Christine, thank you for making it the first and best trip of our life together. I am sure that many more will follow.

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**All the maps, figures and tables were created by the author, unless otherwise stated.**


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# 10. SUPPLEMENTARY RESULTS

## Annex 1: Literature review: Environmental impact of ORV activities

**Impact on soils and water erosion**

The impact on soils and water erosion has been clearly indicated by for example Buckley (2004) and Lovich and Bainbridge (1999). Buckley (2004) also stresses the negative impact on soil life. Soil infiltration rates appear to decrease after compaction of the soil by heavy ORV use and soil density increases as a function of the number of vehicle passes (Lovich and Bainbridge, 1999). In addition, the strong negative impact on the organic matter of a soil can be recognized, even at low intensities of ORV activity (Kutiel et al., 2000). Compaction appears to be one of the major soil erosion aspects as a result of ORV activity as the tyres exert ten to hundred times as much pressure on the soil as a boot (Buckley, 2004; Webb et al., 1978; Nortjé et al., 2012). Compaction of the soil by vehicle tyres can lead to bulk density increase (Webb et al., 1978) and soil crusting and may be recognizable up to a depth of several decimetres (Iverson et al., 1981; Nortjé et al., 2012). Further it should be mentioned that the compaction and bulk density increases logarithmically with number of passes, meaning that the first few passes have the biggest impact (Iverson et al., 1981; Nortjé et al., 2012). It is however difficult to say that compaction will directly lead to an increase in erosion rates, as Goossens and Buck (2008) show the difficult relationship between these two parameters. Compaction can be the start of erosion, but can also – in the case of sandy soils – make the soil less PM10 productive and thus reduce the amount of dust production.

**Impact on vegetation**

The strong negative effect of ORV activity on vegetation is observed by for example Bates (1935), Liddle and Greig-Smith (1975), Kuss (1986), Kutiel et al. (1999) and Kutiel et al. (2000). The tyres cause damage to vegetation types (Buckley, 2004) and cause a decrease in vegetation ground cover, plant mean height, species richness and diversity (Kutiel et al., 2000). Low traffic intensities are already enough to cause long-term changes in the vegetation patterns, affecting immediately by as few as 50 passes (Kutiel et al., 2000; Priskin, 2004). This is also the case for vegetation on beach and dunes (Priskin, 2004; Liddle and Greig-Smith, 1975; Buckley, 2004). Whereas the most damage is caused in the first few passes, successive passes increase the time required for regeneration (Godfrey and Godfrey, 1980). The damage to vegetation appears to be five to thirty times as large as the damage from pedestrians, especially if the vehicle is turning or braking (Buckley, 2004). As a result, the reduced vegetation cover can result in higher erosion rates, as has been described by for example Cerdá (2007) and erosion blowouts and destabilisation of dunes can occur since bare sand is exposed (Priskin, 2003).

**Other environmental impact**

Off-road driving can cause considerable environmental problems as for example in Norway (Tommervik et al., 2012) and Cape Cod, South Africa (Godfrey and Godfrey, 1980). These problems can be more specifically described as road-kill of various fauna species, disturbance of birds, water pollution, introduction of invasive species as weeds (Lonsdale and Lane, 1994). Key concern is the very slow rate of recovery of ecosystems and soils (Lovich and Bainbridge, 1999; Tommervik et al., 2012; Iverson et al., 1981) and the long-term and possibly irreparable damage (Busack and Bury, 1974)

## Annex 2: Detailed information about the MWAC catcher

Measuring the actual emission of a certain vehicle can be difficult as it is relatively expensive. It is therefore important to find a way to estimate the emission, which could be done by estimating the dust transport. This does not give the direct emission rates, but by catching and measuring the entire dust cloud, one can get an idea of the amount of dust that has been emitted (Nolet and van der Veen, 2009). There are mainly two difficulties in measuring the amount of dust that is being transported through the air. Firstly, the amount of dust transported is usually so small, that catching and measuring it forms a challenge in research. Secondly, catching the sediment should take place in a natural matter, that the resulting values give an indication of the actual transport values. Therefore, researchers have been searching for an isokinetic measurer, which means that the measurer as a medium forms a minimal obstacle in the natural processes. In other words, the measurer should not influence the air flow so that extra or less sediment will end up in the catcher (Goossens, 2017). Based on the described criteria and after consulting several experts, the Modified Wilson and Cooke (MWAC) catcher was chosen to be used.

**The Modified Wilson And Cooke measurer (MWAC)**

The MWAC was developed by Wilson and Cooke in 1980 and used regularly in wind erosion and dust research since then. The vertical flux profile of the sediment transport is being sampled on various heights in the dust cloud, by placing several samplers on a pole. The pole is usually placed at around one metre downwind of the road (where the wind direction is perpendicular to the road). Each of the sampler consists of a glass or plastic bottle with two metal tubes on top. The bottles are installed vertically, with the inlet oriented in the wind, and the outlet in the exact opposite direction. Because air can only enter or leave the bottle through the tubes, a difference in air pressure will develop in the bottle when air flows from the inlet tube to the bottle and from the bottle to the outlet tube. Clean air then discharges from the bottle via the outlet and that is present in the air, will be left in the bottle because of the difference in air pressure. As the air flow will not be interrupted, the sampler is an isokinetic measurer which gives transport values that are representative of the actual values.

The total sediment in the vertical flux profile can then be calculated as follows. The amount of dust passing through at the height of each trap is being weighed and recalculated by dividing the caught mass through the inlet area of the metal tube and the time that the samplers have been in the field, leading to a value of dust transport of unit weight per $cm^2$ per unit time. Then, the results of all samplers is plotted in a graph and a curve is drawn that fits the best - in other words, has the highest $R^2$ (Goossens, 2017). By vertically integrating the total dust profile from the resulting curve, the total sediment transport can be calculated. The total height of the profile should be estimated in the field and should be from zero to the top of the cloud, which is usually between 1.5 and 2 metres high when the MWAC pole is placed at 1 metre beside the road. Assumed is that no dust transport takes place above the visible top of the cloud as observed in the field. Logically, it is important to make sure that the dust cloud does not overtop the top sampler, which is avoided in the field by placing the MWAC close by the emission source. The resulting total sediment transport throughout the whole profile can be used to calculate the dust transport per vkt. See figure 12 for the original design of the MWAC.

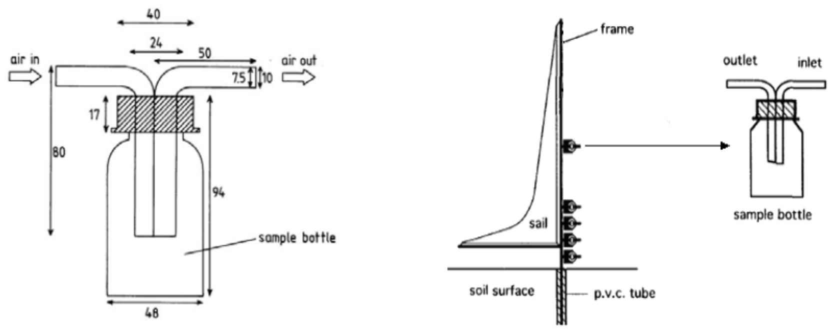


Figure 12 Schematic overview of the MWAC, taken from Goossens and Offer (2000).

In this research, the design of the MWAC was slightly adjusted. As there were no MWAC samplers available, two poles were created with several samplers, keeping the costs as low as possible. The result was a pole with plastic samplers at 10, 20, 40, 80 and 160 cm height from surface level. In the bottles, two metal tubes were placed with a diameter of 7 mm, and glued together to make sure that air could only enter and leave the bottle via the in- and outlet. The samplers were then fixed on the pole using tie-wraps on the right height. As the samplers were plastic bottles instead of glass, cleaning the bottles could not be done in the normal way because the plastic could become electrostatic. We therefore cleansed the bottles with water and weighed them before and after cleansing to get a total amount of dust that was caught. In figure 13, one of the samplers on the used Modified MWAC in the field for this research is shown.

Figure 13 One sampler of the MWAC as used in the field.

The whole design of the MWAC can be created at low costs and are easy to create and install in the field. In addition, it is well suited to measure vertical flux profiles because of the small size of the inlet, and the small bottles form a relatively small obstacle in the wind flow (Goossens et al., 2000). Another reason for choosing the MWAC is its high efficiency in catching an amount of sediment that is representative for the actual dust transport (Goossens and Buck, 2009; Mendez et al., 2011). This efficiency is of high importance for recalculating the raw data to absolute values of dust transport.

There are two weaknesses for the MWAC measurer. The first is that the samplers have such a small inlet, that the amount of sediment caught can be too little to weigh in the laboratory, especially in wind erosion research. However, for dust transport from off-road vehicles, the amount of dust was estimated to be just enough to be caught for analysis (Nolet, 2016). The second weakness is the plastic bottle in this design which was chosen because of its low costs. The plastic can become electrostatically charged and thus needs to be cleansed with water when weighing (Goossens and Offer, 2000; Nolet and van der Veen, 2009). This makes the process of weighing more labour intensive and can make the results less reliable.

## Annex 3: Detailed information about the Inverted Frisbee Dust Deposition (IFDD) catcher

The dust deposition can be estimated by trying to catch the deposition in a way that is representative for the actual deposition rates. It should be noted that the dust deposition is not the same as the accumulation of dust. Deposition refers to the amount of sediment caught in a certain time period, whereas accumulation is the actual remaining sediment at a particular unit surface. As Goossens (2005) describes: *"In physical terms, deposition (or sedimentation) is the sediment flux component directed perpendicularly towards the surface, whereas accumulation is the sum of that component and the component directed perpendicularly away from the surface" (p. 860)*. It is however difficult to measure the actual accumulation, as this depends on the soil type present, texture, presence of aggregates, topography and soil wetness. The measured rates are converted to actual deposition rates using an efficiency factor. This reference is based on the conversion from the method used to a situation where accumulation is the same as deposition, namely the method in which a water body is used. In this water body, sediment will be absorbed and will not fly away anymore. By using this recalculation, different results of dust deposition from different locations can be compared.

Criteria for the method selection were low-cost and reliability. We decided to choose the Inverted Frisbee Dust Deposition (IFDD) sampler, which is a modified version of the Modified Dust Collector measurer (MDCO). Nolet and van der Veen (2009), Sow et al. (2006), Riksen et al. (2016) or Goossens and Offer (2000) offer more detailed information on the IFDD method, and the adjustments that were applied for this research will be described now.

See figure 14 for the design of the IFDD. The IFDD is a smaller and a more low-cost version of the MDCO, although it has the same method of catching sediment. Each Frisbee has a diameter of 24 cm, corresponding to an effective catchment area of 0.045 $m^2$ and is made of iron. In the Frisbee, a sieve is placed with a mesh diameter of 1.3 cm with two layers of marbles on top. These marbles have a diameter of 1.5 cm and serve three main goals, i.e. preventing turbulence to occur around the edge of the Frisbees, preventing deposited sediment to be blown away by the wind, and preventing splashing out of the sediment. In the long term, the marbles will be washed by the rain and the sediment will flow into the Frisbee. The Frisbees are usually placed above ground to prevent splash erosion from occurring (Nolet and van der Veen, 2009), or one could decide to place a layer of artificial grass around the catcher (Riksen et al., 2016). During our experiments, the Frisbees were only used for a short time period with no rain, so we decided to place them close by ground level, to interrupt the air flow as little as possible. After the experiments, the Frisbees were cleansed with water to remove all the sediment and we caught all the water and sediment in bottles to analyse at home. Next, the sediment was allowed to settle a few days and the water was allowed to evaporate. The samples were placed beneath a fan to increase the evaporation speed. After three weeks the samples appeared to be air-dry and were weighed. Then, the total amount of sediment was divided by the deposition area in the Frisbee of 0.045m$^2$ and the total sampling time to come to a value of unit weight per m$^2$ per unit time –e.g. g m$^{-2}$ per hour.

**Figure 14 The IFDD samplers that were used for the research.**

The main goal of using IFDD samplers is to assess the average amount of dust that is deposited within a certain time interval as a result of wind erosion, but it can also be used to assess the length of a dust cloud (Goossens and Offer, 2000). Therefore, we decided to create a transect perpendicular to the road and parallel to the wind direction with several IFDD samplers to assess the decrease in deposition of dust relative to the distance of the source. A more detailed design will be described in the chapter 'Methodologies'.

The IFDD samplers are usually chosen for wind erosion research as they are low-cost and easy to construct. Especially for this research where we want to assess the deposition of dust along a transect, the cost per sampler was important which led to the choice of using the IFDD sampler. Also, the samplers are not susceptible to perturbations caused by humans, animals or any natural processes, particularly during long term measurements, as for example rain water will not stay on top of the sampler so birds will not use it as water basin (Goossens and Rajot, 2008). The efficiency of the sampler is relatively high for a deposition catcher, but low compared to the deposition on a water body (Goossens and Offer, 2000). This is mainly due to the increased turbulence of air flow around the Frisbee. However, when recalculating the resulting values with the efficiency factor of the sampler, one could get good estimations of the actual dust deposition.

## Annex 4: Calculations for standardization of the catchers

Defining the efficiency factor for the **IFDD** turned out to be more complicated, yet even more important than for the MWAC as the catcher appears to be inefficient in the field. The most important reason for this seems to be the turbulence above the Frisbee, as at sufficiently high wind speeds the dust deposition shadow can extend over the whole length of the Frisbee, resulting in very low deposition values (Goossens, 2005). The urgent need of recalculating the raw results was already shown in order to be able to use the results for research (Goossens and Offer, 2000; Mendez et al., 2011; Nolet and van der Veen, 2009). The efficiency of the IFDD in the literature is defined based on dust originating from wind erosion. Since dust as a result of ORV activity appears to be more coarse (Goossens, 2017), the efficiency factor to be used is different. However, Sow et al. (2006) provide us a formula that can be adapted to the coarser grain sizes of the ORV dust. The fractions of the texture classes were taken from the average particle size distribution of the samples. This particle size distribution however varies with distance from the source, as can be seen in figure 15. For fractions smaller than 10µm, the graphs were extrapolated; subsequently, for fractions between 10µm and 89µm, the factors were calculated using the parameter formula; and for fractions larger than 89µm, the same efficiency factor was used as for the 89µm fraction, as turned out that the efficiency seemed to stay constant from that point on.

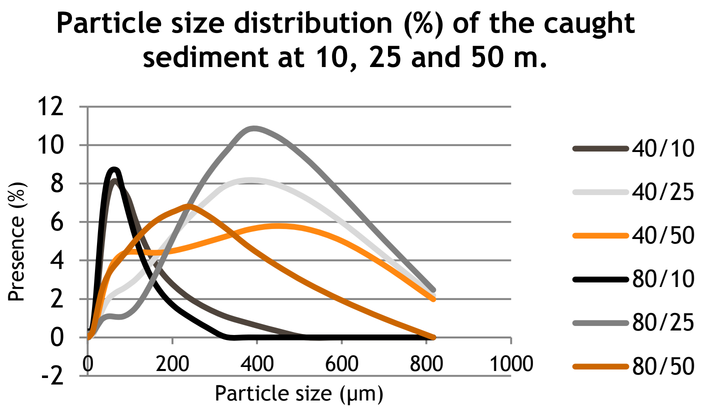


Figure 15: The particle size distribution of the sediment caught at 10, 25 and 50m, showing a variation in the distribution per distance from the source. At 10 metres, especially small particles were caught (<90 µm) , whilst at 25 metres more larger particles were present (+-400µm). The sediment caught at 50 metres appears to show a more average size distribution. More research would be necessary for understanding these differences.

The formula is as follows: $E = au^6 + \mathrm{b}u^5 + cu^4 + d^3 + eu^2 + fu + g$

in which E is the Efficiency factor to be used, u is the variable wind speed during the measurements and the parameters a-g are taken from figure 16 and vary per texture class.

| Class (µm) | Fraction | a | b | c | d | e | f | g |
|---|---|---|---|---|---|---|---|---|
| **0-10** | 0.03325 | - | - | - | - | - | - | - |
| **10-19** | 0.03263 | 0.000255163 | -0.005978909 | 0.054651711 | -0.248940583 | 0.620698435 | -0.965940643 | 1.007721741 |
| **19-31** | 0.06133 | -0.000003829 | 0.000157537 | -0.001118187 | -0.009824746 | 0.15374009 | -0.665992415 | 1.001084163 |
| **31-41** | 0.06732 | -0.000186525 | 0.004252771 | -0.035597454 | 0.122201781 | -0.05885139 | -0.582612175 | 0.998627161 |
| **41-48** | 0.04011 | -0.000198838 | 0.004388285 | -0.034953184 | 0.107821419 | 0.007267178 | -0.681682122 | 1.004421157 |
| **48-56** | 0.04267 | -0.000228302 | 0.004880936 | -0.037335744 | 0.107782159 | 0.032098198 | -0.724080473 | 1.008395234 |
| **56-66** | 0.04382 | -0.000232439 | 0.005047216 | -0.039398163 | 0.118349321 | 0.009898658 | -0.708386873 | 1.003524092 |
| **66-76** | 0.04386 | -0.000205149 | 0.004412196 | -0.033686998 | 0.093580654 | 0.06180491 | -0.750977374 | 1.003775769 |
| **76-89** | 0.04266 | -0.000154213 | 0.00320044 | -0.022705495 | 0.046996557 | 0.151512208 | -0.809806755 | 1.006141656 |
| **>89** | 0.59235 | -0.000154213 | 0.00320044 | -0.022705495 | 0.046996557 | 0.151512208 | -0.809806755 | 1.006141656 |

Figure 16 Overview of the parameters a-g from the formula, given per fraction particle size class (Sow et al., 2006).

The absolute efficiency for the **MWAC** was defined using the results of the particle size analysis and then taken from Goossens and Offer (2000) for wind speeds ranging from 1-5 m $s^{-1}$, and Goossens et al. (2000) for wind speeds ranging from 6-15 m $s^{-1}$. Depending on the measured wind speed in the experiments, the absolute efficiency factor ranges between 1 and 0.8.

The final absolute efficiency factors for the MWAC and IFDD in this research are shown in figure 17 and depend on the wind speed during the measurements.

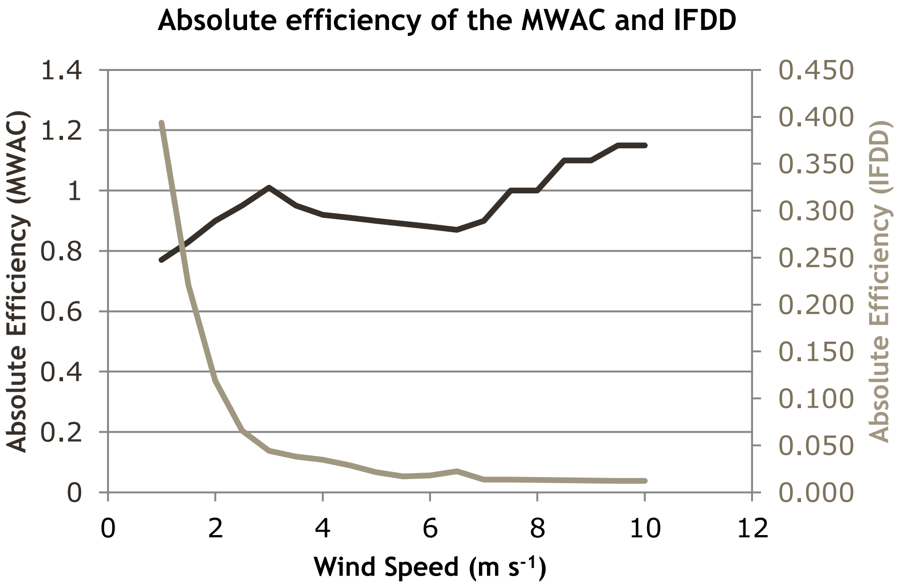


**Figure 17: Absolute efficiency of the used catchers for the research per wind speed, based on grain size analysis and Goossens and Offer (2000), Goossens et al. (2000) and Sow et al. (2006).**

For using the absolute efficiency factors in the results, the wind speeds during the experiments were measured in intervals of 1 minute or 15 minutes. Next, the efficiency per time interval was taken from the graph (figure 17) and then, the average of these efficiency factors is the final efficiency that was used to recalculate the raw results to absolute values. This could be done when assuming that the conditions in terms of dust transport or deposition within one time interval were the same, which may indeed be the case as we produced the dust in a constant way throughout the experiments. The efficiency factors as used for recalculating the results from the research can be found in the supplementary excel file.

## Annex 5: Field observations

**Figure 18 Off-road quad driving as a leisure activity close by Vader Piet, Aruba.**

**Figure 19: Looking at the dirt road with and without traffic during the measurements. Clear dust clouds are visible when traffic is passing.**

**Figure 20: After the first rain storm, the driving tracks from the traffic density experiment already show to be a rainfall collecting point as ponds start to develop.**

**Figure 21 After one month, the driving tracks form waterways where water erosion can take place.**

## Annex 6: Excel file

In the attached Excel file, all the detailed calculations can be found.

## Annex 7: Supplementary recommendations

**Recommendations from earlier research**

Preliminary research stresses the importance of taking into account the impact on environment, erosion and health of off-road vehicular activities. Restoration of areas affected by erosion requires not to only stop the continuing erosion, but also action to restore past damage (Middleton, 1990). The challenge is that the areas where ORV activities take place are often located in or near environmentally sensitive habitats (Lovich and Bainbridge, 1999; Middleton, 1990). This makes it even more important to enhance sustainable management. Managers should keep an eye on the vegetation distribution as described in Bonaire (De Freitas et al., 2005) and Aruba (Oosterhuis, 2016) to come up with location specific measures.

This sustainable management could include several measures. Keeping the vehicular activity on the existing fixed trails is very important, as this will not damage other soils that are now untouched (Kutiel et al., 2000; Nortjé et al., 2012). Limiting the extent and intensity of the impact as much as possible is stressed by Lovich and Bainbridge (1999), given the sensitivity of desert habitats to disturbance and the slow rate of natural recovery. Concentration of the use on a small number of established routes with a minimal total length is recommended by Priskin (2004). For tours, trail sites should be chosen that are less vulnerable towards soil erosion: low slope angles, low upslope trail lengths (Webb et al., 1978).

Negative impact already led to regulations or (partial) exclosure of ORV from national parks, as for example in Sweden (SEPA, 2017) and Iceland (Kaaber, 2017). If they are permitted in parks at all, off-road vehicles should be restricted to a small number of narrow well-maintained tracks, preferably not crossing between catchments (Cater et al., 2008; Kelly, 2013). Critically disturbed areas should be restricted to reduce further degradation (Villareal et al., 2016). Exclosures already resulted in the greatest coverage of vegetation (48% of beach surface) compared to the public access restricted areas (41%). In these areas, 85.5% of the vegetation was lost as a result of all year ORV use (Kelly, 2013).

More specific tips for sustainable quad driving can be described as setting maximum speed levels, avoiding sensitive areas like beaches, driving slower, staying on the roads, avoiding widening the roads and not driving on wet areas, steep terrain or on dunes (Priskin, 2003, 2004; Cater et al., 2008; DOC, 2016).

With regard to human health risks, paving the dirt roads can reduce the nuisance from dust production, as well as restricting heavy vehicles from passing over the dirt roads or implementing a speed restriction (Nolet and van der Veen, 2009). Enforcement of these restrictions is off course of high importance. In-echelon driving is strongly dissuades unless appropriate protection is worn against inhaling the dust (Goossens and Buck, 2014).

**Raising awareness in Aruba**

Looking at the enormous popularity of off-road driving and tours in Aruba, and the potential impact on dust erosion and health, raising the awareness is of high importance. Currently, the Blue Blocks Company is working on this awareness raising and implements several measures together with the Aruba Tourism Authority and the AHATA Environmental Committee as for example restricting off-road driving on the beach, placing signs and preventing rock stacking. The Blue Blocks Company stresses the importance of raising the awareness of caring about the environment, especially for tour operators. Making tourists aware of the environmental issues is important yet difficult, as tourists only spend some time on the island. It is therefore very important to let tour operators help raising the tourists' awareness. As the Blue Blocks Company say in an interview: "Tour operators do not care about the environment. No eco-message is told to the tourists. How unsustainable the tour operators are, can already be observed in their advertisements, as they show a jeep right on the beach" (Beke, 2016). The tour operators appear to be key stakeholders but are currently not taking into account the environmental issues at all, as one of the rental companies told in an interview: "We allow private tours to go through the no-go area between the natural bridge and the park" and: "In the Northern part of the island, near the light house, there are three places where you can cross the dunes to see the sea. Going on the beach is not allowed, but we can't stop tourists to do so" (Company, 2016). Even the 'green' ecotourism companies do not prevent tourists from driving on the beaches. Training of tour operators is thus very important; they are the ones that lead the tourists and need to lead them in the right direction. With regard to health risks, tour operators should inform the tourists to keep distance, or protect themselves. This however seems to be even more important for local people, as they actually live in these conditions.

Most of the time, the rules are not known by tourists, and as the Blue Blocks Company writes on their Facebook page (16 may 2017) that it is *"often not that people want to destroy nature or the environment, they however don't have the proper guidance"*. Quad drivers tend to have the behaviour that can be compared to water: continuously searching for the route of the lesser distance. It is expected that not many tourists will care if the road will be more restricted; off-road driving is already a nice experience, and this rule will make the surroundings even more attractive. Routes change over time as a result of curiosity, or because of looking for better road conditions. Strict guidance through management is thus recommended.