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Modelling aeolian sediment transport in the Badia of Jordan

International Center for Agricultural Research in the Dry Areas
ICARDA

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Abstract

Despite wind erosion processes are well described in literature many vulnerable wind erosion areas as the steppe (Badia) of Jordan have not been studied extensively. The International Center of Agricultural Research in the Dry Areas (ICARDA) has an interest in estimating wind erosion for different agricultural plots in Jordan. A wind erosion research was carried out on a experimental Barley, Water harvesting and Natural grazing plot at Al-Majidyya, (45 km South-East from Amman) Jordan. A measurement campaign consisting of a wind tower with five cup anemometers, three Saltation Detectors, a wind vane and 30 Modified Wilson and Cook (MWAC) sediment catchers were established during summer (June-Sept) 2011. No wind erosion storms were recorded by the anemometers (Max wind velocity = 7.37 m/s) and no saltation was recorded by the Saltation Detectors. The sediment of the MWAC catchers were insufficient for data analysis. The cover and roughness characteristics of the three experimental plots were different, whereby the Water harvesting plot had a higher aerodynamic roughness ($Z_0 \approx 17$ cm) compared to the other two plots ($Z_0 \approx 10$ cm) due to the presence of vegetation lines consisting of ridges and shrubs planted in furrows. The ridges on the Barley plot were parallel with the predominant wind direction (West) and therefore no obstacle for the wind.

Three datasets were obtained, besides wind and soil data of Al-Majidyya (UU dataset) also weather data from the past of the Al-Muwaqar and Queen Alia Airport (Amman) stations were provided. A detailed historical wind analysis in combination with wind velocity comparisons were made. According to ICARDA and The National Center for Agricultural Research and Extension (NCARE),the wind erosion storm season was from June-September, however the historical wind analysis showed a potential wind erosion season from October-March.

The Revised Wind Erosion Equation (RWEQ) model was used to estimate mass transport and soil losses for each experimental plot. Four periods of the translated Al-Muwaqar dataset were selected and used in the RWEQ Model. These selected periods were based on the number of potential wind erosion days whereby $U_2 > U_{threshold}$. This resulted in four periods from January-

March of the years 2002,2003,2004 and 2011. The Barley and Natural grazing plot showed the highest mass transport rates, $Q(x)_{barley} = 0-3.0(kg/m)$ and $Q(x)_{Naturalgrazing} = 0 - 1.0(kg/m)$ for the potential wind erosion period of ≈ 10 days in 2002. However the Jan-March period of 2004 showed the highest average mass transport rate per 10 minute timestep, meaning that for a valid period of 5 days already a $Q(x)_{barley} = 0 - 1.86(kg/m)$ was obtained. The Barley plot was the most erodible plot followed by the Natural grazing plot which was a third of the wind erosion quantities compared to the Barley plot due to lower erodible soil factors. However the Water harvesting plot showed almost no wind erosion due to the low Combined Crop factor caused by the vegetation lines. The wind erosion quantities of the Water harvesting plot were $> 90\%$ reduced compared to the quantities of the Barley and Natural grazing plot.

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Chapter 1

Introduction

1.1 The Jordan steppe (Badia)

The West Asia and North Africa (WANA) region are mostly covered by rangelands of the arid and semi-arid zone of the Middle East and North Africa [Ziadat et al., 2006]. The increasing water scarcity is threatening the economic development and the stability of many parts of the WANA region. At present, agriculture accounts for over 75% of the total consumption of water [Karrou et al., 2011]. The Badia (steppe) covers large parts of the rangelands: around 80% of Jordan, 75% of Iraq, 90% of Saudi Arabia and 55% of Syria [Ziadat et al., 2006].

Around 81% of Jordan is covered with Badia which represents approximately 72,600 km^2 [Karrou et al., 2011]. The Jordan Badia is subdivided into three geographical areas: Northern steppe, Middle steppe and the Southern steppe [Oweis et al., 2006]. Historically refers the *Badia* name to the region where Bedouins live, and the badia is still inhabited by the Bedouin people today [Oweis et al., 2006]. The human population is about 185,000 [FAO, 1994]. The steppe has potential for the production of animal food and provides sufficient vegetation for grazing. The desert has limited grazing resources and receives less than 100 mm rain per year [Oweis et al., 2006]. However the steppe has significant economic importance, for instance the Jordan steppe is capable of producing sufficient fodder for around 800,000 sheeps for the whole year [Al-Junaidi, 1996].

The Jordan steppe is representative of the vast drier environments in the WANA, and the increased droughts and water shortages in Jordan has increased the interest of scientist to explore the possibility of using these dry areas [Al-Junaidi, 1996]. The Jordan steppe holds numerous natural resources, including mineral deposits, surface and groundwater, renewable natural rangeland, and cultivated land suitable for agriculture and livestock production [Oweis et al., 2006]. Within the rangelands the most important vegetation zone is located in the North-East part of Jordan. This zone covers 67% of Jordans land surface. The vegetation in the Jordan Badia includes shrubs and short grasses. Irrigated crops like vegetables and fruit orchards are found in the Badia as well [Karrou et al., 2011]. The main land use type in the North East part of Jordan is grazing by sheep on natural vegetation areas. Irrigation using groundwater is applied at isolated locations, and mainly used to grow tree crops like olives. However a few farmers cultivate barley without irrigation, but usually the rainfall is insufficient to produce a reasonable grain yield. Most of the years this barely biomass can only be used as fodder for the sheep [Sterk, 2011].

The Badia region of Jordan is characterized by its harsh climate [Ziadat et al., 2006]. The rainfall season in Jordan occurs from October to May and the mean annual rainfall ranges from $0 > 600mm$ (figure: 1.1 [Allison et al., 1998], [Al-Sirhan, 1998], with an annual average of 100-150 mm [IFA, 1993],[IFA, 1997]. The highest rainfall occurs in the highlands of Jordan, a narrow belt lying east of the Dead Sea and extending north to the Syrian border [Oweis et al., 2006]. From the highlands and extending eastwards, the climate becomes increasingly dry (figure 1.1). The temperature regime is Thermic and the heat in the summer reaches a peak during August, while January is usually the coolest month. The fairly wide ranges of temperature during a twenty-four-hour period are greatest during the summer months [Allison et al., 1998]. The daily mean minimum is obtained by averaging the minimum temperature per day over one year. For Jordan this mean minimum temperature is about 10°C. The daily mean maximum is 24.5°C. On average a daily temperature of 17.5°C is reached. The absolute minimum and maximum temperatures could reach 5°C in winter till over the 46°C in summer, respectively [Allison et al., 1998].

1.2 Land degradation in the Badia

63.2% of the Jordan steppe receives less than 50 mm of rainfall per year [Oweis et al., 2006], therefore shortage of water is a major problem. However 1.1 million ha of the steppe uses collected rainwater on a efficient way to make agriculture practices possible [IFA, 1997].If rain falls, it falls on crusted soils with low infiltration rates, resulting in surface runoff and uncontrolled paths of water flow [Oweis et al., 2006], [Karrou et al., 2011].The limited rainfall is lost either through direct evaporation from the soil surface or through run-off, which if not intercepted, collects in wadis (rain buffer zones) or pans where it eventually evaporates. The result is land degradation caused by erosion, poor vegetation cover, and serious water stress

[Oweis et al., 2006]. Sufficient vegetation is an important factor to stop land degradation. Vegetation allows water and air to penetrate deeply into the soil resulting in less water erosion and food and refuge for wild animals and livestock. Sufficient vegetation will act as a barrier between the desert and the rural and urban areas [Oweis et al., 2006].

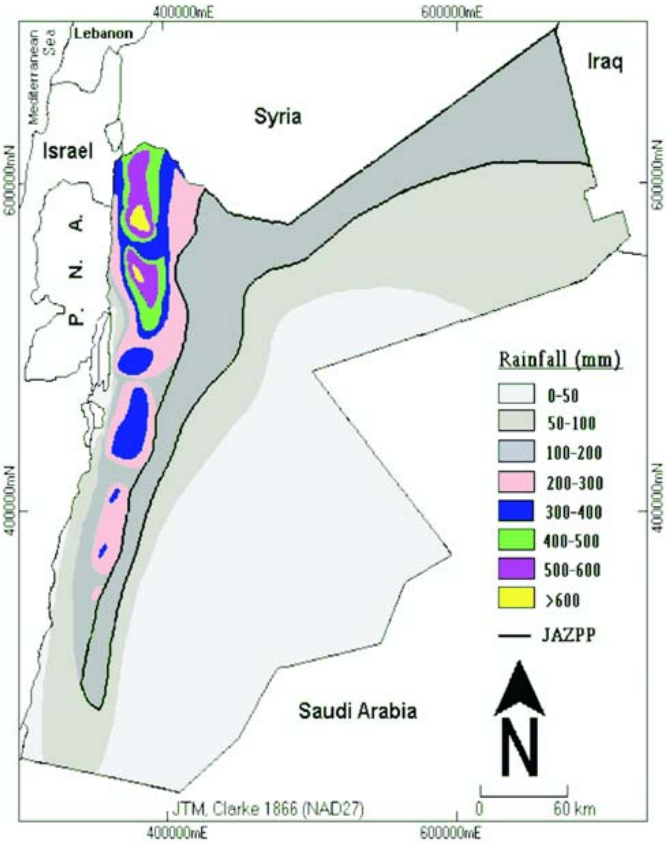

Figure 1.1: Mean annual rainfall in Jordan. (Source: [Oweis et al., 2006])

Apart from water erosion, the Jordan Badia is also subjected to wind erosion.This process is characterized by transporting soil particles by the forces of the wind and occurs on locations where winds are strong, and unprotected soils are dry and loose. According to [Khresat et al., 1998] erosion by wind and water is considered the major cause of land degradation in north-western Jordan. However, studies on wind erosion quantification in other parts of Jordan were not done so far. Hence, it is generally unknown how serious the land degradation caused by wind erosion is in the Jordan Badia.

The main goal of this study was:

Measure and model wind erosion quantities for several experimental plots in the Badia of Jordan.

This was done by achieving the following objectives:

- Characterize soil and cover properties of the study area.
- Analyze historical wind data.
- Measure wind erosion quantities in relation to different surface types.
- Model wind erosion quantities with the Revised Wind Erosion Model (RWEQ).

Chapter 2

Wind erosion

Wind erosion is the process of wind forced movement of soil particles. In other words the force of the wind is able to take up loose soil particles, (ranging from very small particles <60-70 μm till quite large particles >500 μm), carry them away and eventually deposit them elsewhere [Parigiani, 2009]. By definition, wind erosion is the removal of soil material, whereas sedimentation is the deposition of wind-blown material [Sterk, 2011]. This definition is divided into three phases of particle movement; detachment, transport, and deposition. Detachment occurs when the wind force against soil particles increases enough to overcome the force of gravity. Once detached, moving particles may collide with surface particles and detach the latter. The detached soil particles are then subject to transport by the wind, either through the air or along the surface. Eventually the wind velocity decreases and soil particles are deposited. Deposition typically occurs in areas with low wind velocities like furrows or vegetated areas where the wind velocity is slowed down due to friction. Deposition also occurs along the edge of fields in ditches, fence-rows, or behind barriers such as windbreaks [Presley and Tatarko, 2009].

The transport of soil material by wind-blown forces can occur in three different transport modes (figure 2.1); surface creep, saltation and suspension [Bagnold, 1941].

- **Saltation**, these particles have a size between 50-500 μm. Saltation particles jump and bounce over the surface, reaching a maximum height of approximately one meter but the main particle mass moves just above the soil surface [Sterk, 2011]. The saltation mode could be seen as the main driving force of wind erosion because the bulk of total transport, roughly 50-80% is moved by saltation [Lyles, 1988]. When saltation particles return back to the surface they may abrade themselves or other particles due to impact. The impact of saltation

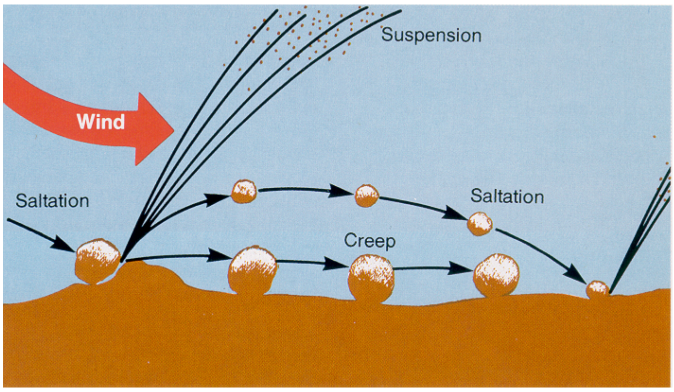

Figure 2.1: Transport modes in wind erosion.

will also initiate movement of particles [Lyles, 1988]. According to Chepil and Woodruff (1963), wind erosion will only occur if saltation size particles are present in the soil [Parigiani, 2009].

- **Surface creep**, these are the largest particles (500-1000 μm) that roll or slide over the surface. Creep particles are too heavy to be lifted from the surface in normal erosive winds. Creep particles are pushed, rolled and driven by the impacts of spinning particles in saltation [Presley and Tatarko, 2009].

- **Suspension**, these are the smallest particles, <100 μm and will be kept in the air due to the turbulent nature of the airflow [Parigiani, 2009]. These particles are raised in the air due to the collision of saltation particles with the surface.

The factors that influence the wind erosion process are atmospheric conditions, soil properties, land surface characteristics and land-use practice (e.g. farming, grazing and mining). All natural and geological factors will interact between each other during a wind erosion event [Shao, 2000]. In the field of agriculture, loose dry and uncovered sandy soils are most vulnerable to wind erosion. Wind erosion damages soil, crops and the environment by reducing soil productivity, affecting plant emergence and quality, yield, and increasing dust particles in the atmosphere (air pollution) [Shao, 2000]. The pollution in the atmosphere may cause reduced visibility and deposition at unwanted places (infrastructure, habitable zones, etc.) with resulting economic drawbacks [Mohammed et al., 1995] [Parigiani, 2009].

Wind erosion quantification is obtained by wind erosion instruments. According to [Lyles, 1988], saltation accounts for 50-80% of the total transport,therefore most wind erosion instruments are designed to quantify the saltation transport mode. Wind erosion instruments are distinguished in two classes. The first class are passive instruments, non electric instruments usually sediment catchers. An example is the Modified Wilson and Cook (MWAC) sediment catcher described by Sterk and Raats, (1996). The second class of instruments are active (electric signal needed to obtain physical quantity) instruments like Saltiphones described by Spaan and Van den Abeele, (1991) and Saltation Detectors (SALDEC) designed by the laboratory of physical Geography Utrecht University [Thuy, 2011].

Several wind erosion models are available for wind erosion quantification. The common models that qualify for wind erosion at a field scale are: the wind erosion equation (WEQ) [Woodruff and Siddoway, 1995], the revised wind erosion equation (RWEQ) [Fryrear et al., 1998] and the wind erosion prediction system (WEPS) [Hagen, 1991]. The WEQ predicts wind erosion for yearly periods but not for small time intervals. A disadvantage is that users are not allowed to identify critical periods with serious wind erosion. According to Fryrear (1998) and Hagen (1991), RWEQ and WEPS are able to make a yearly and short period estimate, allowing the model operator to change management settings within a cycle period or even within a crop growth season or for just one or several erosion events [Buschiazzo and Zobeck, 2008]. Several attempts have been made to calibrate these models in the USA [Fryrear et al., 1998],[Zobeck et al., 2000].Each model uses a long-term climatic database but each model implements this data in a different way [Buschiazzo and Zobeck, 2008]. All models use wind speed and wind direction data as a base. However all models are different in time step and RWEQ and WEPS use extra input data as soil and vegetation observations. The use of more sources of input data will results in a liable and better estimation for RWEQ and WEPS.

Chapter 3

Materials and Methods

3.1 ICARDA

The International Center for Agricultural Research in the Dry Areas (ICARDA) carries out research projects of water management with the goal to integrate water harvesting techniques in existing agricultural systems to improve vegetation cover and reduce land degradation [Sterk, 2011]. One of these projects takes place in the Jordan Badia. The ICARDA water management project works with a local partner in Jordan, the National Center for Agricultural Research and Extension (NCARE) to develop, test and adapt improved water management options at the farm and watershed levels [Ziadat et al., 2006]. ICARDA carries out different experiments of water harvesting techniques in order to decrease drought, increase water availability to plants and enhance rainwater productivity in drier environments. Water harvesting techniques will control the amount of runoff and therefore controls water erosion in these areas. The water management project has the long-term goal to integrate water harvesting techniques in existing agricultural systems to improve vegetation cover and reduce land degradation. ICARDA also has an interest in quantifying the effects of the water harvesting techniques on wind erosion.

3.2 Study area

The experimental work was carried out in a place called Al-Majidyya, a small village 45 km southeast of the capital Amman. The Al-Majidyya site (17-ha) has an altitude range of 820-846 m and topography comprises a gentle slope (north-eastern), a moderate slope (south-western), and a flood plain and main gully between the two slopes the slope has a range of 2-30% [Karrou et al., 2011]. This site was selected for the water harvesting project in November 2006 after a study on the bio-physical and socioeconomic behavior, participative workshops, meetings, and field visits in the Jordanian Badia [Karrou et al., 2011].

The soil at this site has a silty loam to silty clay or loam and is low in organic matter [Sterk, 2011]. It has a high calcium carbonate ($CaCO_3$) content [Karrou et al., 2011]. The water infiltration rate of such soils is low (4-20 mm/h) [Karrou et al., 2011] and the soil surface is often crusted, leading to high surface runoff [Sterk, 2011] resulting in a higher risk of water erosion. Soil samples were taken by NCARE in 2011, the results are shown in table 3.1.

Table 3.1: Physical and chemical properties of the top soil (0-25 cm) of each experimental plot in Al-Majidyya 2011.

Plot	No. of soil samples	*Particle Size distribution* Clay %	Silt %	Sand %	Organic matter	Total Nitrogen	PH value	Salinity (EC) value	Texture
Barley	20	23.53	52.15	24.32	1.78	0.11	8.07	1.62	Silt loam
Water Harvesting	28	29.09	51.06	20.14	1.64	0.11	7.85	5.29	Clay loam
Natural grazing	19	30.59	49.21	20.20	1.86	0.07	7.83	3.56	Clay loam

The site consists of three plots with sizes of 120 $m \times 35$ m and different land management types. The first plot consists of a barley field which is harvested and plowed (arise of ridges) at the end of the growing season. The second plot has water harvesting structures. The last plot consists of a natural grazing field.

The vegetation cover on the Barley and Natural grazing plot was low and consisted only of sparse cover of some grasses and shrubs. The water harvesting site consisted of systematic placed shrubs (*Atriplex halimus*) planted in furrows along the contours with 1-3 meter space between two shrubs [Sterk, 2011]. All furrow lines were curved in the shape of a horseshoe on a flat slope between 2-8%, the distance between each furrow line was approximately 8-15 meter [Sterk, 2011] and there were 8 furrow lines in total. The dimensions of the shrubs varied from several cm till over 2 meters in diameter. The ridges were approximately 35 cm high and the furrows were 80 cm wide and 15 cm deep [Karrou et al., 2011].

3.3 Historical wind data analysis

A historical wind data analysis from 1983-2012 was made to see if,when and how many wind storms took place during that period. Two weather datasets (close to study area) were provided by NCARE and ICARDA, a third dataset was coming from a meteorology station (wind tower) at the field site.

The most complete dataset was obtained from Queen Alia-Airport, Amman and provides measurements from 1983 (construction date) till mid 2012. The Queen Alia-Airport dataset contains values for the most important weather quantities including average and maximum wind velocities. Each average wind velocity (knots) was daily recorded, whereby the average include several till up to 24 readings per day. The maximum sustained wind velocity (knots) for a unknown time interval was recored just once per day. Unfortunately there was no wind direction data recorded for this dataset.

The second dataset was coming from a weather station called Al-Muwaqar. The Al-Muwaqar station is approximately 15 km located form the study area and provides data for the last decade. This station contains data for average, minimum and maximum wind velocities (km/h) and wind direction ($\circ$). Data is recorded every 10 minutes resulting in 144 records per day.

The final dataset (UU station) provides wind velocities at different heights (m/s) in combination with wind direction data ($\circ$). Specifications about the station and data-logger are found in section 3.4.

Three data comparisons were made for the (June-Sept) 2011 period: 1)Al-Muwaqar vs Queen Alia-Airport, 2)Al-Muwaqar vs UU station, and 3)Queen Alia-Airport vs UU station. The comparisons were made in order to test the equality of the datasets. When a difference was found, a test was done to view if the difference was constant over the period. An comparison will validate the correctness of each dataset. Striking data like low or high values can be checked and measurement/log errors are noticed. Day,week or month patterns can be compared with patterns in the past to look if they were still the same or if they were changed over time.

From each dataset the statistical measures like mean, standard deviation and the maximum value for wind velocity and wind direction were calculated. Statistical comparison methods like the Mean absolute error (MAE) (equation 3.1) [Hyndman and Koehler, 2006] in combination with the Root mean squared error (RMSE) (equation 3.2) were calculated to verify the difference in means for each combination: $\mu_{dataset_1} - \mu_{dataset_2}$ [Armstrong and Collopy, 1992].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_{1,i} - x_{2,i}| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \tag{3.1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}} \tag{3.2}$$

Where e_i is the absolute difference of measurement i of dataset 1 $x_{1,i}$ minus measurement i of dataset 2 $x_{2,i}$ and $(x_{1,i} - x_{2,i})^2$ is the squared difference of two dataset measurements $x_{1,i}$ and $x_{2,i}$ of equation 3.2. n is in both equations the total number of measurements. Note, that we call the equations *differences* instead of *errors*, normally these equations are used to test predictions and estimations.

Both methods can be used together to diagnose the variation in the differences of two datasets. The RMSE will always be larger or equal to the MAE, the greater difference between them, the greater the variance in the individual errors in the sample. If the RMSE equals the MAE, then all the errors are of the same magnitude meaning that all differences are constant. A perfect match (RMSE=MAE) will never happen in reality, however a small difference indicates a constant offset between two datasets. A constant difference between each dataset pair illustrates equal wind velocity measured under slightly different circumstances. The constant offset in two analyzed datasets are caused by different sensor heights and/or different topographic structures (hills,vegetation and roughness).

The historical wind analysis was performed for the Al-Muwaqar and Queen Alia-Airport station. Both datasets were plotted against time to identify potential wind erosion storms in the past. A threshold wind velocity was calculated for both datasets based on the UU data in combination with soil and wind datasets from other studies. The calculated thresholds were adapted for each station to take account for differences in sensor heights, wind velocity averaging time and topographic locations.

3.4 Wind characteristics

During the field research wind velocity and wind direction were measured by the use of a wind tower (UU Station) (figure: 3.1). The wind tower consisted of six wind sensors, 5 cup anemometers for measuring the wind speed at 5 different heights above the soil surface at 1.0, 2.0, 3.0, 4.0 and 5.0 m, and one wind vane for measuring the wind direction. Each sensor on the wind tower was connected with a data logger (Campbell CR10) reading each sensor with a 10 seconds interval and storing the average value each minute. During the study the tower was installed in each plot (Barley,Water harvesting and Natural grazing) with one month intervals. This was done to obtain the friction velocity (m/s) and the aerodynamic roughness length (m) for each plot surface type. These parameters were related with the wind velocity profile as described in section 3.4.1. The wind tower positions were chosen such that the locations were not sheltered by unrepresentative field objects and free of any form of disturbances.

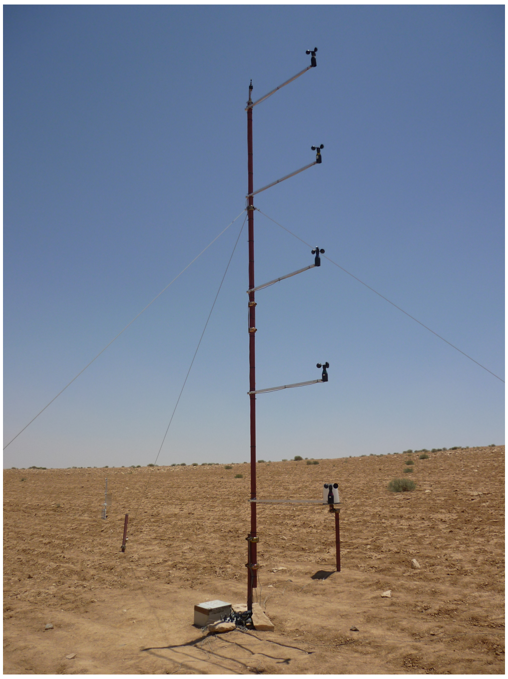

Figure 3.1: Wind tower with 5 Anemometers and one wind direction sensor at the top.

3.4.1 Logarithmic wind velocity profile

The wind at high altitude above the soil surface, unrestricted by barriers or objects, is known as *"free stream"* air flow and moves more or less parallel to the surface. The wind near the surface affects the soil and vegetation, these removes energy from the wind and result in a lower wind velocity. The average forward velocity near the soil surface is lower than in the free stream. The velocity increases as the distance above the surface increases [Presley and Tatarko, 2009]. This velocity gradient is known as the "*wind* *velocity profile".*

The following equation was used to describe the average wind velocity profile:

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{3.3}$$

Where $U(z)$ is the mean wind velocity ($m\ s^{-1}$) at height $z(m)$; z_0 is the aerodynamic roughness length (m); k is von Karmans constant ($= 0.4$); u_* is the friction or shear velocity ($m\ s^{-1}$). u_* is defined as $u_* = \sqrt{(\frac{\tau_0}{\rho})}$ [Stull, 1988], where τ_0 is the average shear stress ($N\ m^{-2}$) at the surface and ρ is the air density ($kg\ m^{-3}$). The shear velocity vector lies parallel on the air/soil interface and is in opposite direction of the wind direction vector. With a minimum of two observations of average wind speed at different heights, both u_* and z_0 can be determined by linear regression using least squares estimation. To quantify the amount of wind erosion the parameter u_* is mostly used instead of $U(z)$, because u_* is not dependent on the height $z(m)$ and so easier to use in calculations.

A large z_0 value means that the terrain is aerodynamically rough and so the corresponding wind speed is relatively low due to the high friction. Therefore the parameter z_0 provides direct information of the roughness of each surface type and describes indirectly the potential risk of erosion.

3.5 Wind erosion Quantification

3.5.1 Saltation Detector

The SALDEC is a simple device with a piezo-electric sensor inside a plastic tube. The sensor senses saltation particle impacts with the tube, and the created pulses are counted and stored in the same data logger as used for the wind speed and wind direction measurements. The SALDECs were used to determine the start, duration and intensity of sediment transport. The wind speed and saltation activity were measured simultaneously to determine the relation between wind speed and sediment transport [Thuy, 2011]. From such data the threshold conditions for sediment transport can be determined with great accuracy [Sterk, 2011].

3.5.2 Sediment Catchers

Thirty MWAC sediment catchers (figure 3.2), were used for measuring aeolian mass flux densities. These instruments consist of a series of traps mounted on a rotating central pole. A sail (wind vane) is attached at the central pole to orientate the catcher in the direction of the wind. Each trap consists of a plastic bottle with two glass tubes entering through the cap of the bottle. The inlet is orientated in the wind direction for catching the sediment, the outlet is in opposite direction so that air can escape from the bottle. The diameter of the inlets are 8 mm and the opening is 50.3 mm^2 [Parigiani, 2009]. Several traps can be placed at different heights. Normally 5 traps are used to get a detailed relation between mass flux density and height. The overall trapping efficiency was calibrated in a wind tunnel by taking the ratio between the measured mass transport rate with a MWAC catcher and the actual mass transport rate obtained in the wind tunnel with known sediment mass before and after a run. The MWAC has a trapping efficiency of 54.4% [Sterk, 1993].

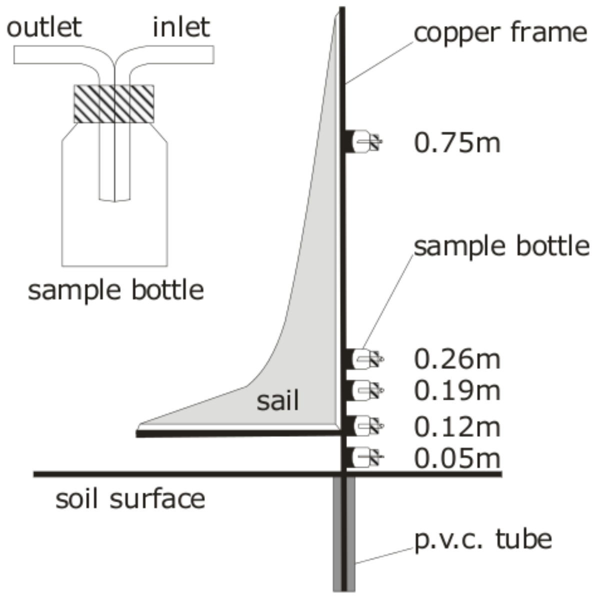

Figure 3.2: Modified Wilson and Cooke sediment catcher with sample bottle. (Source: Parigiani, 2009)

3.5.3 Modelling mass densities

The MWAC catchers provide data of horizontal mass flux density ($kg\ m^{-2}s^{-1}$) at different heights. A curve is fitted through the observations to describe the vertical profile (z) of the measured mass flux densities [Zingg, 1953],[Sterk and Raats, 1996] (equation 3.4).

$$q(z) = q_0 \left(\frac{z}{\sigma} + 1\right)^{-p} \tag{3.4}$$

Where $q(z)$ is the horizontal mass flux density ($kg\, m^{-2}\, s^{-1}$) at height $z(m)$ and q_0 is the mass flux density at height $z = 0$. The parameters σ and p are respectively the length scale and a dimensionless exponent. Values for q_0, σ and p are determined by fitting equation 3.4 through the measured mass flux densities.

Integrating the profile over height from $z = 0$ to $z = 1$ and correcting for the trapping efficiency of the catcher (54.4%) results in a total mass transport rate Q_{tot} in ($kg\ m^{-1}s^{-1}$) at each point of sampling. If this value is multiplied by the duration of the storm, obtained from the SALDECs, then this new Q value is equal to the mass of material moving below 1 m height that passed a 1 m wide strip perpendicular to the wind direction during a wind storm. The unit of Q becomes $kg\, m^{-1}$ [Sterk and Raats, 1996].

3.6 Experimental Setup

The wind erosion measurements were conducted from June till September 2011 at the research site in Al-Majidyya.

At each plot (Barley,Water harvesting and Natural grazing) 10 MWAC were installed (figure: 3.3). After each month the wind tower was moved to the next plot (July $\rightarrow$ Barley Plot, August $\rightarrow$ Water harvesting Plot and September $\rightarrow$ Natural grazing Plot) to obtain the z_0 and u_* values of the three different surface types.

The dimensions and the experimental setup for each plot was similar and covered a size of ± 30 by 45 meters. All MWAC catchers were placed in a 3 by 3 grid with one catcher centered at the top (figure: 3.3). In this way each wind direction had three sediment catchers in one line resulting in sufficient redundancy. The average distance between two catchers (B-E) in the Y direction was ± 20 m and the average distance between two catchers (B-C) in the X direction was ± 14 m. The distance between the top catcher A with catcher C was ± 10 m. All plots were oriented in West-East direction and the predominant wind direction at the benchmark site is shown by the blue arrow. The difference between the Water harvesting plot with the other two plots was that the soil of the Water harvesting plot was crusted and densely covered by vegetation, whereas the other plots had some stones and shrubs as cover.

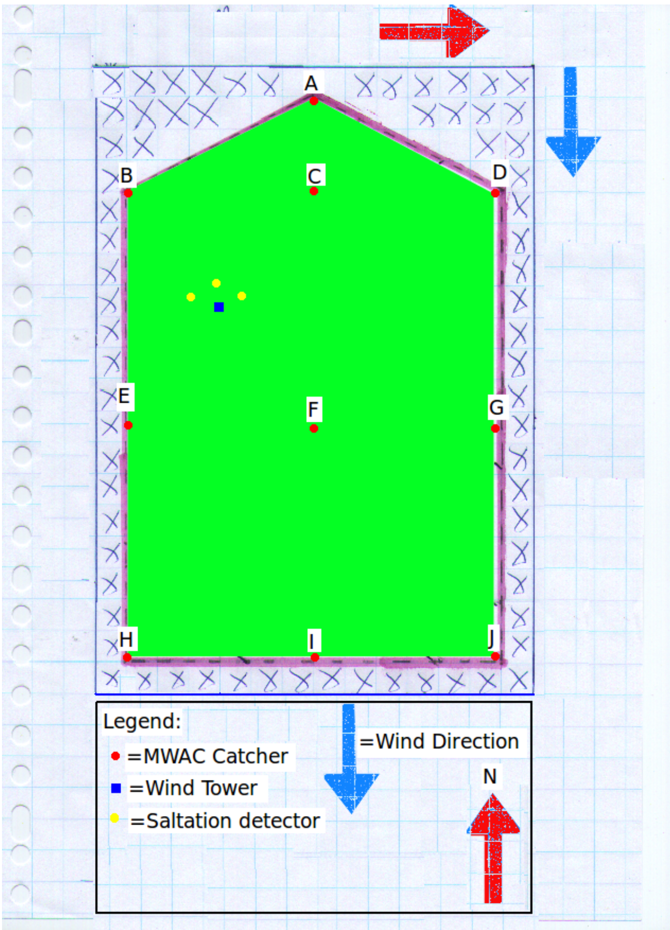

Figure 3.3: Experimental setup on each Plot (Barley,Water harvesting and Natural grazing)

3.7 Soil and Cover characteristics

The wind erosion process is also dependent on surface cover (vegetation and stone) and soil texture (% of clay, silt and sand). Both were determined for each of the three agricultural plots. Soil samples were taken and analyzed by the National Center for Agricultural Research and Extension (NCARE). Cover characteristics like the quantity, density and dimension of stone and vegetation objects were obtained by making detailed field observations.

3.7.1 Soil Properties

From each plot samples were taken homogeneously over the field, in which they were analyzed for soil texture on the depths 0-5 or 0-25 cm. The soil samples were tested for the presence of Clay, Silt, Sand, Organic matter, Salinity and Calcium Carbonate ($CACO_3$), as well as for nutrients like Nitrogen and Phosphorous.

3.7.2 Surface cover

Surface cover was obtained by drawing vegetation and stones at a detailed field sketch. The presence of stones was expressed as a percentage of occurrence in a predefined area. For this a visual estimation of each plot was made and compared with photographs with pre-defined cover percentages stone cover in.

The low vegetation cover of the Barley and Natural grazing plot was suited to measure the shrub dimensions by hand of shrubs that are within the borders of the MWAC catchers. The high vegetation cover of the Water harvesting plot needed a different approach, therefore several representative shrubs with small and large dimensions were measured which resulted in one average shrub size for the Water harvesting plot. The position of the furrow lines were optically estimated and detailed marked in a field sketch. The percentage of vegetation occurrence in the Water harvesting plot was estimated by multiplying the total length of all furrow lines with the width dimension of the average shrub in combination with the dimensions of the ridge and the furrow of the shrub. In this case the cover existed of the shrub, ridge and furrow of the shrub combined as one block of cover. The block cover percentage was obtained by dividing the block cover area over the total area of the Water harvesting plot (formula: 3.5).

$$A = \frac{tot_{cov}}{tot_{area}} \cdot 100\% \tag{3.5}$$

Where A is the occurrence percentage of the cover object, tot_{cov} the total area of the cover object and tot_{area} the total area of the plot.

3.7.3 Roughness

The aerodynamic roughness parameter z_0 was obtained for each plot by using least squares estimations in combination with equation 3.3. This parameter was used to determine the roughness of the different plots and indirectly the potential risk of wind erosion. This parameter is purely based on wind velocity measurements at different heights.

Other roughness parameters were used like ridge height (cm), ridge spacing (cm) and ridge orientation for the Barley plot. These field parameters were obtained for modelling purposes. The roughness (vegetation lines) of the Water harvesting plot was characterized as vegetation cover and the roughness of the Natural grazing plot was visually estimated.

3.8 Wind erosion Modelling

3.8.1 RWEQ model

For the wind erosion research in Al-Majidyya from June-September 2011 was made use of the Revised Wind erosion Equation model (RWEQ). The RWEQ model is a field scale wind erosion model [Fryrear et al., 1998]. It is spatially explicit (1 dimensional) meaning that it provides wind erosion rates as a function of distance $Q(x)$ in the field [Fryrear et al., 1998]. The model area should be homogeneous circular or rectangular with temporal intervals of 1-15 days, where own defined intervals are possible as well, [Youssef et al., 2011]. Note that each simulated plot needs a non-eroding boundary from where sediment transport starts to develop. Without a non-eroding boundary the model is not valid [Youssef et al., 2011].

The model input is based on four physical modules, respectively Weather, Soil, Vegetation and Roughness [Youssef et al., 2011]. The results (Factor values) of all modules are combined to obtain the wind erosion quantities as the average soil loss ($S_L; kg\ m^{-2}$) and the aeolian mass transport rate ($Q(x); kg\ m^{-1}$) for one specific agricultural plot. Each module depends on simple equations which represent the Factor value/s for that module. The following list and figure 3.4 give a summary of the most important calculations steps resulting in the model output values of (S_L and $Q(x)$. For a complete and detailed description of all model equations see the RWEQ manual of Fryrear et al., (1998).

- Weather Module = Weather Factor W_F (kg/m)
  $W_F = f$(Wind factor,air density,gravity constant, soil wetness, snow depth)
- Soil Module = Soil Crust Factor (S_{CF}) & Erodible Factor (E_F)
  $S_{CF} = f$(Organic matter,Clay)
  $E_F = f$(Organic matter,Clay,Silt,Sand,Calcium Carbonate)
- Vegetation Module, = Crops On Ground factor (C_{OG})
  $C_{OG} = f$(Flat cover, Standing silhouette, Canopy)

- Roughness Module = Single soil roughness factor (K_{tot})
  $K_{tot} = f$(Random roughness, Orientated roughness)

The combined module factors are used to determine the main model output equations.

Total aeolian mass transport ($Q(x)$; $kg\, m^{-1}$) is equal to:

$$Q(x) = Q_{max} \cdot \left(1 - e^{-\left(\frac{x}{s}\right)^2}\right) \tag{3.6}$$

Where x is the distance (m) from the non-erodible boundary, s is the critical field length (m) and Q_{max}; ($kg\, m^{-1}$) is the maximum transport capacity defined as:

$$Q_{max} = 109.8 \cdot (W_F \cdot E_F \cdot S_{CF} \cdot K_{tot} \cdot C_{OG}) \tag{3.7}$$

The Critical field Length s (m) is defined as the distance at which the 63% of the Q_{max} (kg/m) is reached and is calculated by:

$$S = \mu_{sa} \cdot (W_F \cdot E_F \cdot S_{CF} \cdot K_{tot} \cdot C_{OG})^{-\mu_{sb}} \tag{3.8}$$

Whereby, μ_{sa} and μ_{sb} are RWEQ calibration parameters with their ($\mu_{sa} = 150.7$ and $\mu_{sb} = 0.3711$) default values based on field experiments in the USA [Fryrear et al., 1998].

Finally the average soil loss (S_L; $kg\, m^{-2}$) is calculated by:

$$S_L = \frac{2 \cdot x}{s^2} Q_{max} \cdot e^{-\left(\frac{x}{s}\right)^2} \tag{3.9}$$

3.8.2 RWEQ into PcRaster

PCRaster is a program language designed for environmental dynamic modelling [PCRaster, 2011]. PCRaster is part of the GIS family and mainly used in Geo-sciences. PCRaster provides spatial and temporal functions that can be used to construct many physical models.

The original RWEQ model was implemented in a non spatial program and does not have the flexibility of varying the module outcomes over time and location (x,y), therefore Youssef (2011) implemented the RWEQ into PCRaster. Each RWEQ module in PCRaster can be implemented in a spatial/temporal way what makes the model outcome more accurate and reliable.

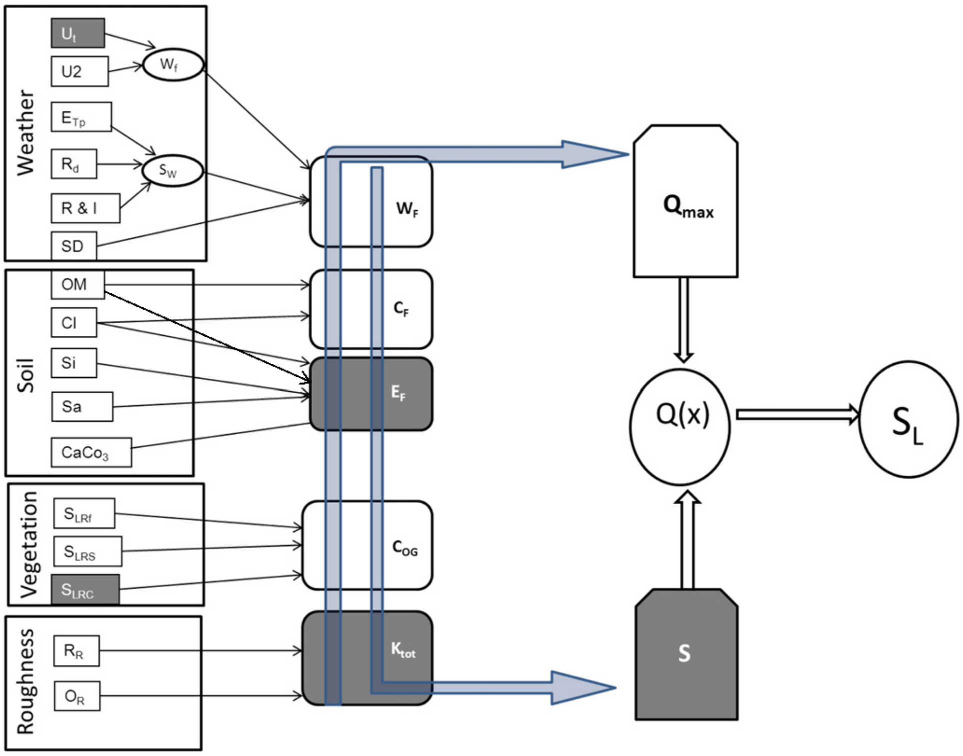

Figure 3.4: Illustration of calculation steps for soil loss S_L and mass transport $Q(x)$ in RWEQ. U_t, threshold velocity at 2 m height; $U2$, wind speed at 2 m; W_f, wind factor; E_{Tp} ,potential relative evapotranspiration; R_d, number of rainfall/irrigation days; $R\&I$, rainfall and irrigation; SD, snow depth; SW, soil moisture; W_F, weather factor; OM, content of organic matter; Si, content of silt; Cl, content of clay; Sa, content of sand; $CaCO_3$, calcium carbonate;CF, crust factor; E_F, erodible fraction; S_{LRf}, flat residue; S_{LRs}, standing residue; S_{LRc}, crop cover; C_{OG}, combined crop factors; R_R, random roughness; O_R, orientated roughness and K_{tot}, single soil roughness factor. The highlighted boxes with white letters contains calibration parameters (Source: [Youssef et al., 2011])

Additional adaptations were made by Youssef (2011) and included, simulation of the transport over the field boundaries and the timestep interval. In this way the timestep becomes equal to the timestep of the observations. This means that for every record in the weather dataset a mass transport rate is calculated. Default RWEQ calibration parameters were used from field research in the USA in 2004 [Van Pelt et al., 2004]. Parameter values were subsequently adjusted to obtain reliable values for the Jordan field conditions.

Chapter 4

Results and Discussion

The fieldwork in Al-Majidyya (Jordan) took place from June 26 till 18 September 2011. The UU station, (wind tower in combination with the Saldecs and a tipping Bucket) was operational on June 29 till the last field-work day (18 September). During this period each sensor was recorded every minute and stored in the Campbell CR10 data logger. The sediment from the MWAC catchers was collected every 2 to 3 weeks with a total of 4 sets.

4.1 Soil Surface Properties

A soil crust was only present in the Water harvesting plot. The Natural grazing consisted of broken crust parts due to frequent presence of livestock. The cover percentage of shrubs on the Barley and Natural grazing plot was $< 0.2\%$. This value is rounded for model calculations and set on 0% vegetation cover for both plots. However the surrounding area of the Barley and the Natural grazing plots consisted of more shrubs with a changing topography and increasing slopes. There was significant vegetation cover on the Water harvesting plot. Using equation 3.5, the estimation of the total area of all vegetation lines was $\approx 20\%$. The presence of stone cover was difficult to measure because of the large amount of stones ($\approx 5 \times 5$ cm), therefore visual estimations were done and compared with predefined cover percentages as defined by Herweg (1996). After repeating the cover estimation several times, it resulted in 10% stone cover for each plot.

4.2 Wind erosion

A detailed analysis of wind velocity was made to study the occurrence of wind erosion in the summer of 2011. In the dataset windspeed (at 2 m) was never exceeding 8.0 m/s. According to work of Parigiani (2009) and Sterk (1999) wind velocities thresholds of $\pm 8\, m/s$ are needed to initiate saltation transport. The highest wind velocity measured in the entire UU dataset was

7.37 m/s on July 8, 2011 at 17:11. Similar wind velocities ($> 7m/s$) were selected (at 2 meter height) to study SALDEC data to see if wind erosion had happened during the field work (Appendix: A.1). No significant saltation occurred at wind speeds $> 7\,m/s$ on any of the plots. There were some but no continues SALDECs observations that indicates the start/end time of a wind erosion event. The total mass of sediment in all 30 MWAC catchers in the field during the measurement period was $<$ 7.9 gram so on average 2.6 gram for one typical plot and only 0.26 gram per MWAC catcher. This was assumed negligible for such a long (3 months) measurement period and insufficient for proper data analysis. It was concluded that wind erosion at the Al-Majidyya site was insignificant during the experimental season.

4.3 Wind characteristics

The wind dataset of the UU station consisted of 1 minute average wind velocities in combination with wind directions and was recorded for 79 days (3 days missing due to logger problems). Figure 4.1 shows the daily average wind velocity (m/s) and the corresponding average wind direction for the UU weather station during the measurement period of 2011 in Al-Majidyya.

The average wind velocity at 2 meters throughout the measurement period (June-Sept 2011) was 3.18 m/s ($\sigma = 0.69\ m/s$), which was on average too low for wind erosion. The corresponding average wind direction was 266° and fairly constant for daily averages ($\sigma = 13°$). The highest wind velocity period (day) was observed at the end of June but still insufficient to initiate particle movement. Two peaks below the 240° direction were observed indicating a significant difference in wind direction ($> 2\sigma$) compared to the average wind direction. The corresponding wind velocities for these peaks show low values as well (figure: 4.1).

A closer look to standard deviations of the wind directions showed that wind velocity between 0-1 m/s had a σ of 116°, and with a wind velocity of 6-7 m/s $\sigma = 13°$ and became close to the standard deviation of the daily average period. Different wind velocity intervals were studied and wind directions caused larger deviations when wind velocity was decreased and it became really variable for wind velocities $< 1m/s$ (table: 4.1).

Figure 4.2 shows a 10 days period of wind velocities measured between 3 and 13 August, whereby a 24 hour wind velocity cycle was shown with lower obtained velocities in the morning (round 00:00 hour) and evening (round 22:00 hour). The higher velocities occurred during the day with a peak around 12:00 hour. The wind direction data followed a similar pattern as wind

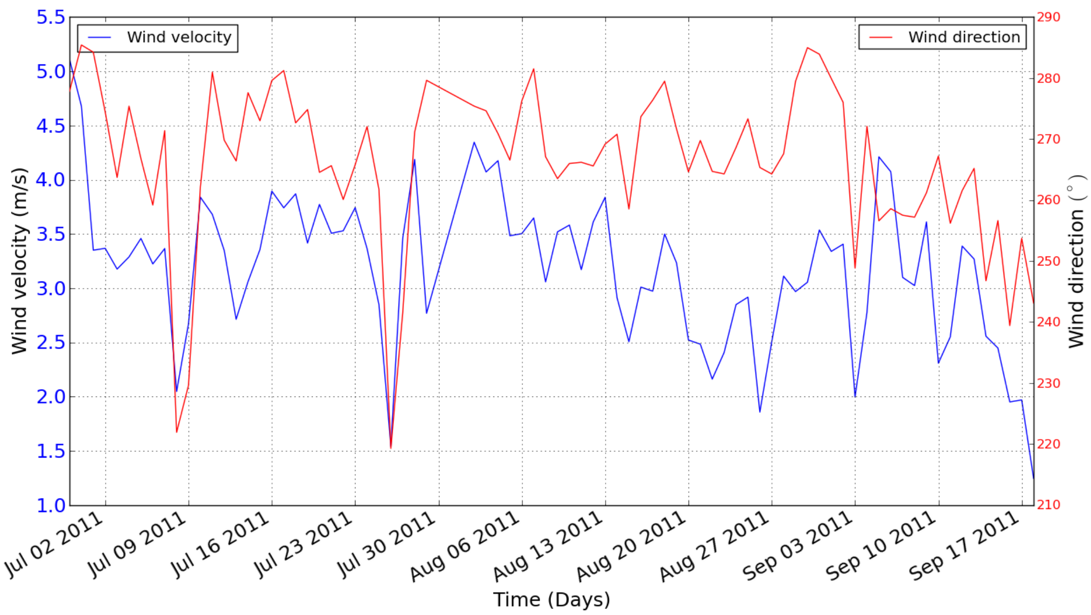

Figure 4.1: Daily average wind velocity (m/s) and wind direction during the measurement period 2011 at Al-Majidyya. Wind velocity was recorded at 2 m height.

Table 4.1: Averages and standard deviations of the raw wind direction data (1 minute records) for different wind velocity intervals

Velocity interval	**Mean**	**Std.dev**
$0-8$ (m/s)	266	39
$0-1$ (m/s)	208	116
$1-2$ (m/s)	261	51
$2-3$ (m/s)	260	33
$3-4$ (m/s)	263	29
$4-5$ (m/s)	274	25
$5-6$ (m/s)	281	16
$6-7$ (m/s)	283	13
$7-8$ (m/s)	284	12

velocity. According to the Royal Dutch Meteorological Institute (KNMI) these patterns were caused by differences in day temperature. Early in the morning (a few hours after sunrise) wind velocity will reach his minimum velocity. However a few hours after the sun reaches it's highest position, wind velocity reach a maximum (Max wind speed = 7.37 m/s at ± 17:00 hour) [KNMI,2011]. When the evening begins, wind direction starts to turn. This change in wind direction is related to greater friction of the wind over land [KNMI,2011]. According to the wind results and the information of the KNMI, wind velocity and wind direction were dependent on the change in daily temperature.

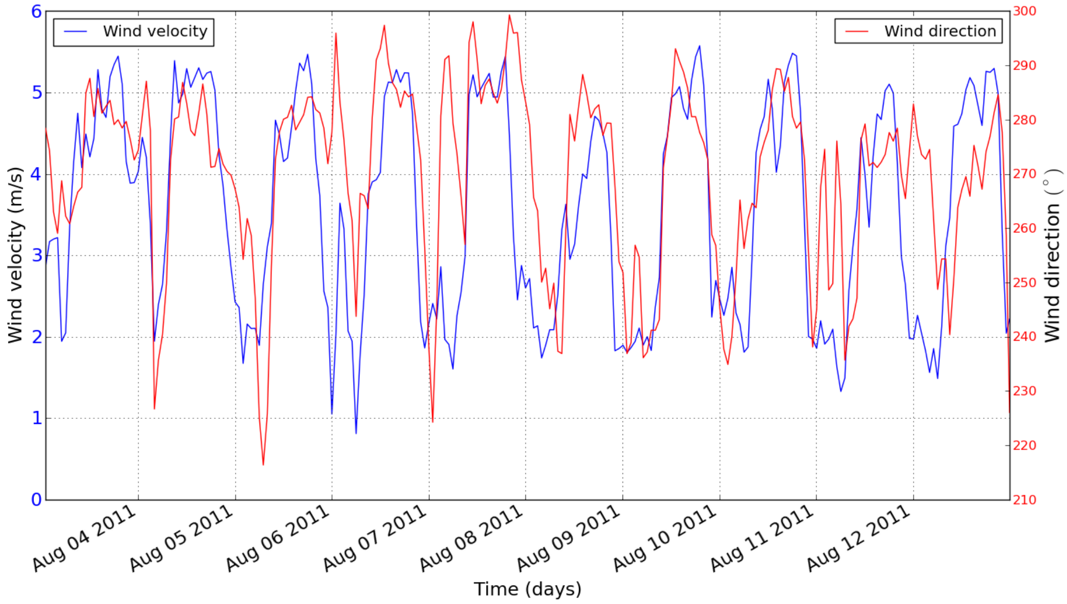

Figure 4.2: Hourly averaged wind velocities and wind directions of the UU station during 3-13 August 2011

The UU station was placed in each plot for one month to obtain the wind profile parameters z_0 and u_*. The calculation of the wind profile parameters was based on 30 minute average wind velocities at 2,3,4 and 5 meter height above the surface, by using linear regression. Only the regression results with a squared correlation of $R^2 > 0.90$ and a relatively stable ($\sigma < 5°$) wind direction were used to obtain the average z_0 parameters for each plot. Whereby the Barley and Natural grazing plot showed similar roughness, respectively $z_0 = 0.098\, m$ and $z_0 = 0.11\, m$. These results confirmed that the ridges on the Barley plot had nearly no influence on the wind velocity because the wind direction was parallel to the ridges. The Water harvesting plot showed significant more roughness due to the presence of vegetation lines which resulted in a $z_0 = 0.17\,m$.

Each surface type is characterized by it's own z_0 value, depending on the surface roughness created by vegetation, stones and ridges. Vegetation is an important cover factor that influences wind erosion. A flat soil with no vegetation will have a z_0 value of around 5 mm. More vegetation will results in a z_0 value of several cm up to 25 cm [Oke, 1987]. The parameter u_* increases with wind velocity, and thus no characteristic value can be given.

The Barley and Natural grazing plots showed similar outcomes ($\approx 10\,cm$) however the Water harvesting plot showed a significantly higher aerodynamic roughness because of the presence of shrubs and furrows on the plot. The Barley and Natural grazing plots are relatively flat but have relative high z_0 values. The reason for this lies in their surrounding topography of shrubs, rocks and slopes that influence the wind velocity within the Barley and Natural grazing plots. A constant wind direction with a $\sigma < 5\circ$ will give a reliable estimate of z_0. As an example, wind will react differently when it flows parallel or perpendicular to ridges. For a rough soil there is theoretically zero wind velocity near the surface where $z(m) = z_0$ however in reality the wind at this point no longer follows a mathematical logarithm, the wind becomes turbulent and so wind velocities $> 0\,m/s$ are still present.

4.4 Historical wind analysis

Figure 4.3 shows the wind velocity of all wind stations (June-Sept.2011). Queen Alia Airport shows the largest wind velocities compared to the other two stations, the dataset contains values from July 1983 till June 2012. Unfortunately the observations are recorded with only a few readings per day what makes this dataset less useful for smaller time steps analysis. Differences between the average wind velocity of each station are caused by unknown circumstances as surrounding topography and sensor height.

4.4.1 Comparison between stations

A summary of some statistical measures for each station dataset during the measurement period of 2011 is shown in table 4.2. The standard deviations of the daily averaged measurements of UU and Al-Muwaqar stations were more or less similar. However the standard deviation of Queen Alia airport show 1.5 to 2.5 times larger values compared to the other two stations. The daily average observations of the airport station were made from 20-24 readings. The difference in wind velocity between two contiguous days were larger compared to the other two stations and reach or cross sometimes the observation value of the UU station. Due to the unknown observation height and surrounding area it's difficult to conclude what causes the larger standard deviation exactly.

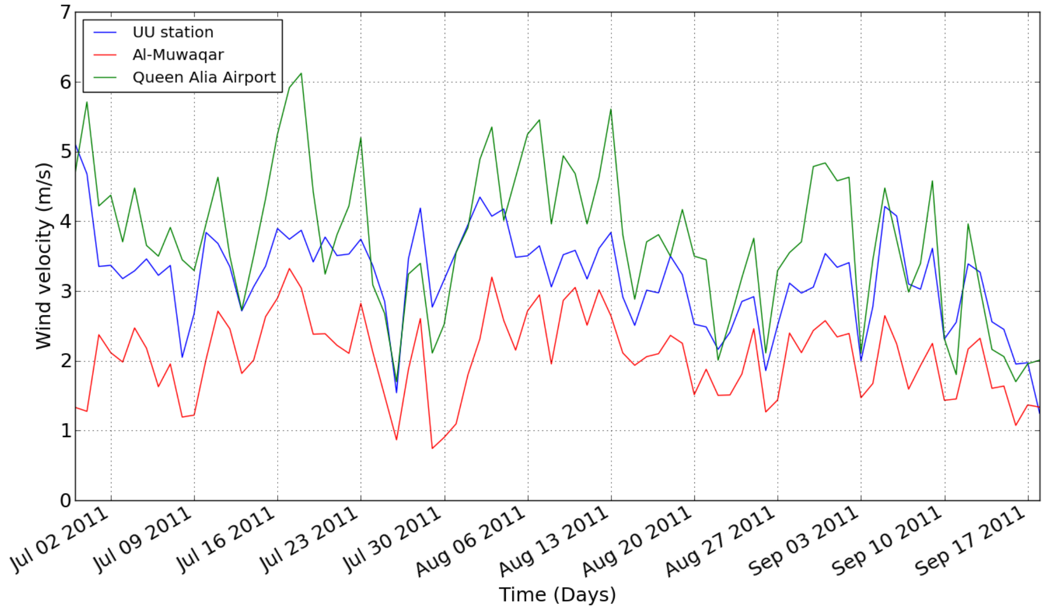

Figure 4.3: Daily average wind velocity during the measurement period for the UU (Wind tower), Al-Muwaqar and Queen Alia Airport (Amman) Weather-stations. Whereby wind velocity of the UU station was observed at 2 m height

Table 4.2: Daily average wind quantities (mean,standard deviation and maximum) during the measurement period June-September 2011. Whereby wind velocity of UU station was observed at 2 m height.

Weather quantity	**UU Station**			**Al-Muwaqar Station**			**Airport Station**		
	Mean	**Std.dev**	**Max/Min**	**Mean**	**Std.dev**	**Max/Min**	**Mean**	**Std.dev**	**Max**
Wind velocity (m/s)	3.18	0.69	7.37	2.05	0.58	7.53	3.74	1.06	6.12
Wind direction °	266	13	285.4/219.3	252.4	59.63	317.92/23.0	X	X	X

The Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) was calculated for a statistical comparison between each station. Table 4.3

shows these statistical measures in combination with the ratio of both measures $\frac{MAE}{RMSE}$ and with the standard deviation of all individual $\frac{X_1}{X_2}$ ratios to check the MAE/RMSE relation. The statistical measures were taken from the daily average wind velocity during the measurement period (June-Sept.) 2011.

Table 4.3: The results of the RMSE, MAE, $\frac{MAE}{RMSE}$ and Std.dev $\frac{X_1}{X_2}$ based on daily wind velocities of the stations UU, Al-Muwaqar and Queen Alia Airport during the measurement period 2011

Statistical Method	**UU vs. Al-Muwaqar**	**Al-Muwaqar vs. Airport**	**UU vs. Airport**
RMSE (m/s)	1.23	1.83	0.90
MAE (m/s)	1.13	1.69	0.56
$\frac{MAE}{RMSE}$	0.92	0.92	0.62
Std.dev $\frac{X_1}{X_2}$	0.13	0.11	0.17

The average wind velocities per day for each station contain relatively small differences. The ratios of $\frac{MAE}{RMSE}$ of each comparison show for 82-92% similarity meaning that the differences between each dataset were close to constant and RMSE $\approx$ MAE (section 3.3). The results of the standard deviations of the ratio $\frac{X_1}{X_2}$ verify the $\frac{MAE}{RMSE}$ outcome. The standard deviations of $\frac{X_1}{X_2}$ shows outcomes close to zero (table: 4.3) indicating that the ratios between two datasets were constant. The anemometer height of the UU station was set at 2.0 meters above the surface, which is a representative measure height for wind erosion. The sensor height of the Al-Muwaqar and Queen Alia Airport station including their surrounding topography were not known, therefore it was not possible to make a correction to reduce the offset even more.

4.4.2 Historical comparison

The Al-Muwaqar station provided 10 minutes data from 2001 till 2011. Unfortunately in some years one or more months were missing due to station problems or wrong analysis procedures. The dataset of Queen Alia Airport goes back to 1983 and is updated every month. This station provides daily values based on 1-24 observations per day with an average of 19 observations per day, unfortunately some day records were missing and observations times were not known.

A historical data analysis was performed to see if,when and how many potential erosive storms took place in the past. Figure 4.4 shows data of Queen Alia Airport and Al-Muwaqar for the last decades. Both datasets

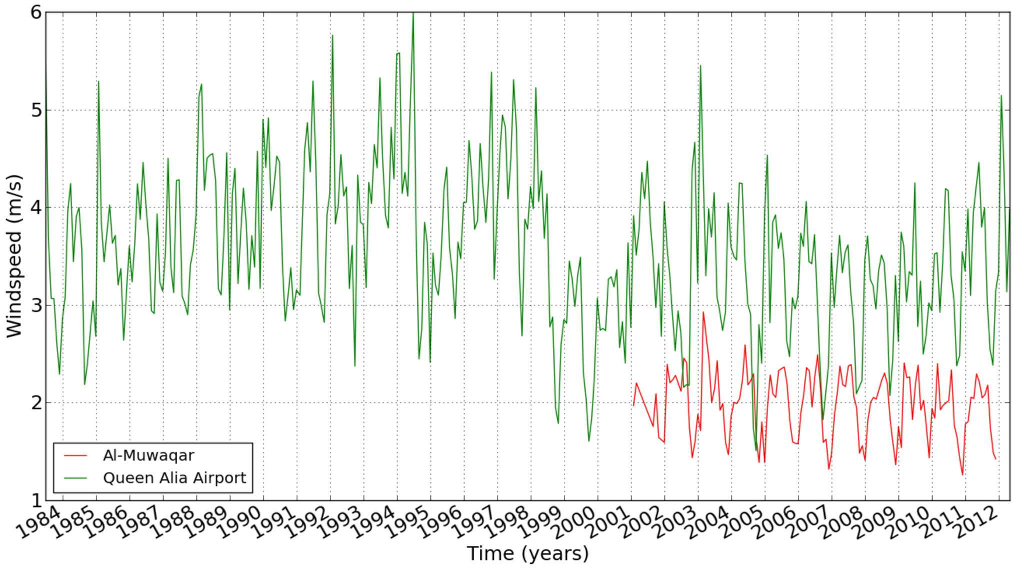

Figure 4.4: Monthly average wind velocities from 1983-2012 of the Al-Muwaqar and the Queen Alia Airport weather-stations.

were averaged every month to give a clear and summarized look about wind velocities in the past. The Al-Muwaqar data was significant lower in wind velocity than the data from Queen Alia Airport. However there was a constant offset between them if we look at the ratio of $\frac{MAE}{RMSE} = 0.92$ of (table 4.3) what means that MAE $\approx$ RMSE indicating that approximately all observations differences were constant. However this was only calculated for three months in 2011. A second control test was made for all months of 2009 resulted in $\frac{MAE}{RMSE} = 0.78$ what still confirmed the consistency between both sets. Assuming that the observation circumstances remained constant over time, then the consistency was valid for all observations from 2001-2011.

To see if erosive wind storms happened in the past all average wind velocities above a certain threshold were selected from Queen Alia airport and Al-Muwaqar data. A wind erosion study in North East Spain 1996 [Sterk et al., 1999] had similar soil surface properties and sensor heights as the research in Al-Majidyya in 2011. In the field experiment in Spain saltation transport started above a wind velocity threshold of 8 m/s (one-minute data) for dry soil circumstances. The highest one minute wind velocity observed by the UU station at a sensor height of $2m$ was 7.37 m/s whereby no wind erosion occurred. Therefore the decision was made to use a wind velocity threshold similar to the North East Spain experiment (8 m/s).

The sensor heights of Queen Alia airport and Al-Muwaqar were not known ($5-25\,m$ above surface) which resulted in an unknown wind velocity threshold. Therefore, the Al-Muwaqar and Airport data were converted to new datasets, with average conditions corresponding to the UU wind velocity data at Al-Majidyya. The constant offset (MAE) of each dataset was calculated (table: 4.3) and used to translate both, the Al-Muwaqar and Queen Alia Airport dataset to approximate the values of the UU data. So Al-Muwaqar was translated by adding a MAE of 1.13 m/s to the original data and Queen Alia Airport was translated by subtracting a MAE of 0.56 m/s from it's original data (figure 4.6).The wind velocity threshold for wind erosion is dependent on the averaging time of the measured wind velocities [Stout, 1998]. When the averaging time increases the wind velocity threshold will decrease. To determine the wind velocity threshold for the converted Al-Muwaqar data use was made of an equation based on the *time fraction equivalence method* of Stout and Zobeck (1997). This equation describes wind velocity thresholds as a function of averaging times [Stout, 1998]. The equation was used to extrapolate the one minute UU threshold of 8 m/s to a velocity threshold based on 10 minutes (Al-Muwaqar). The equation of Stout and Zobeck (1997) was plotted for some experimental (Wind and saltation) data on a semi-log paper, with on the x-axes the averaging time (T in seconds) and on the y-axes the wind velocity threshold (U_t m/s). By choosing two points on this line, the direction coefficient (a) was obtained by filling in the UU wind threshold of 8 m/s for 60 seconds coefficient b was solved as well (equation: 4.1).

$$U_t = -0.8643 \cdot ln(T) + 11.54 \tag{4.1}$$

The translated equation 4.1 was obtained and now useful to extrapolate the 1 minute UU threshold to 10 minutes. This resulted in a wind velocity threshold of 6.0 m/s for 10 minutes. However equation 4.1 was not used for obtaining a wind velocity threshold for an averaging time of 24 hours because of the long extrapolation time and extremely low threshold value (1.71 m/s). Therefore the threshold of Queen Alia Airport was obtained by comparing the potential wind erosion days of Al-Muwaqar, with the Queen Alia Airport wind velocities. By plotting the selected $U_2 > 6.0 = U_t$ wind velocities of Al-Muwaqar (10 minutes records) between 6.0 and 6.3 m/s again the same days of the daily averaged wind velocity of Queen Alia Airport, resulted in a wind velocity threshold of $\approx 5.2\,m/s$ for 24 hours (figure: 4.5).

Figure 4.7 shows the results of the selected wind velocities of Queen Alia airport. Queen Alia airport had a selected range of 5.2 m/s till less then

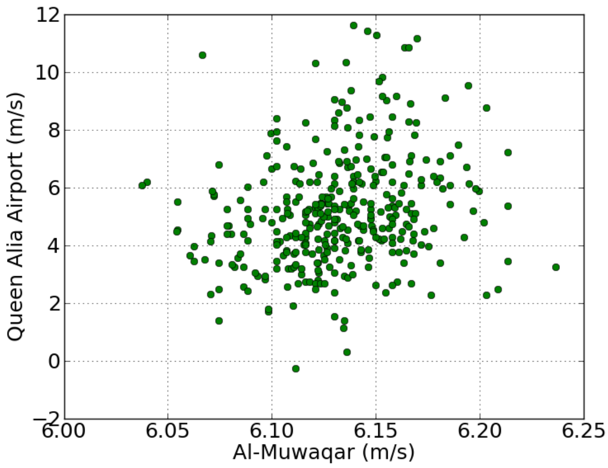

Figure 4.5: Selected wind velocities $U_2 > 6.0 = U_t$ of Al-Muwaqar vs. Daily wind velocities of Queen Alia Airport, whereby a minimum of six wind velocities $> 6.0\, m/s$ were required to be selected.

20 m/s and figure 4.8 shows the selected wind velocities of Al-Muwaqar between 6.0 m/s and 20 m/s. The Queen Alia Airport data was selected when the daily observation passed the threshold velocity of 5.2 m/s. The data of Al-Muwaqar was selected when a minimum of six observations per day passed the wind velocity threshold of 6.0 m/s. This minimum value of six observations was chosen because one high observation does not automatically mean a wind erosion event. A minimum of six observations will indicate that the wind was at least one hour able to initiate particle movement.

The results of figure 4.7 and 4.8 show the potential wind erosion days with corresponding wind velocities. The green scatter points show wind velocities > 5.2 m/s. The sum of the green points (Airport data) shows that 1214 days with potential wind erosion occurred with a wind velocity > 5.2 m/s. This is $\approx$ 11.6% of all wind velocities measured from 1983-2012. A minimum of six valid ($U_2 > 6.0 = U_t$) observations were needed per day to be selected. The Al-Muwaqar data shows more valid days compared to the Airport data because of it's 10 minutes based records (more data in time). The sum of the Al-Muwaqar potential wind erosion days shows that 17891 days were above the 6.0 m/s wind velocity threshold value, this is $\approx$ 3.4% of it's total set of all wind velocities measured from 2001-2011.

According to ICARDA and NCARE, the erodible season is from June-

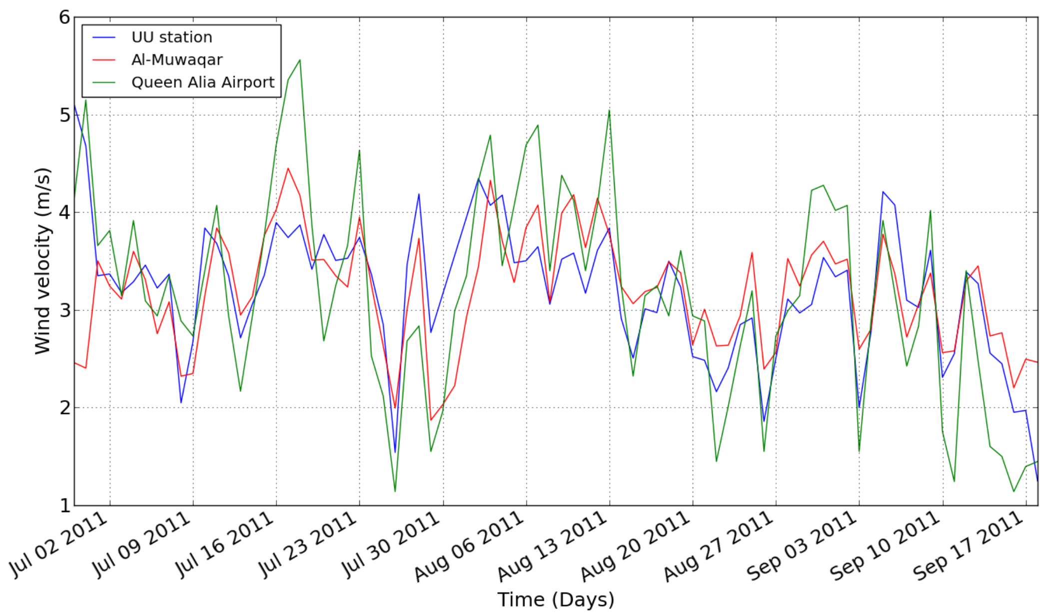

Figure 4.6: Daily averaged wind velocities of the original UU, translated Al-Muwaqar and translated Queen Alia Airport stations.

September [Sterk, 2011], however figure 4.7 and 4.8 shows a different potential wind erosion season. Of the 1214 selected storm events of Queen Alia Airport ≈ 59% (714 events) falls in October-March period. Of the 17891 storm events of Al-Muwaqar ≈ 69% (12318 events) falls in October-March period. However wind erosion conditions are in winter time less optimal due increasing precipitation [Karrou et al., 2011] which results in wet soils with stronger cohesion forces between soil particles what makes soils less erodible for wind erosion. If no precipitation falls in the October-March period, wind erosion will still be possible. Even if some precipitation fall down, high evaporation rates will dry out the top soil quickly and the soil becomes vulnerable for wind erosion again.

4.5 RWEQ model results

4.5.1 Model plot characterization

All plots have similar sizes and were equal in experimental setup. However difference in soil and topographic objects characterize each plot individually. Because there was no land survey data (geometric data) available, the

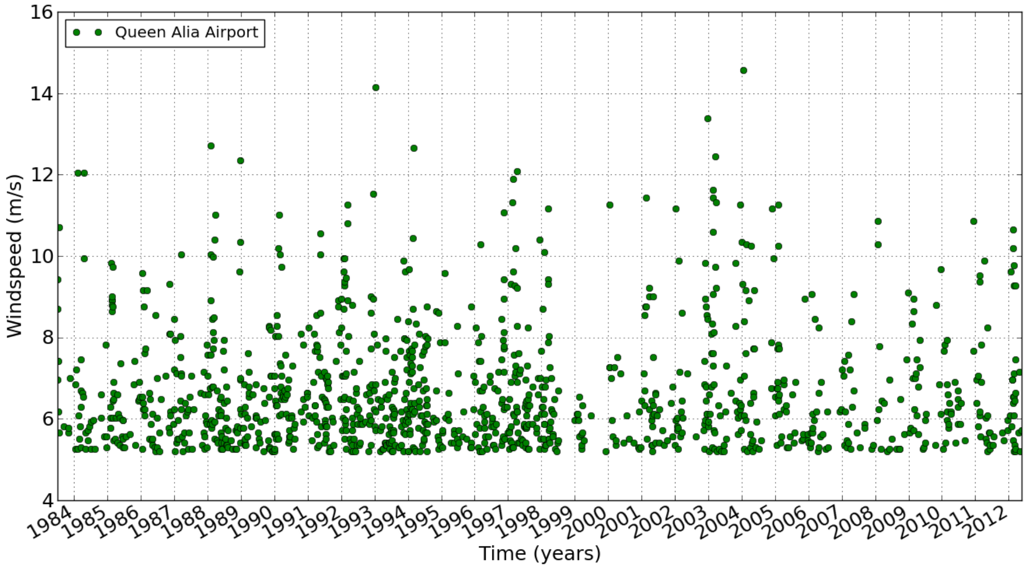

Figure 4.7: Selected ($U_2 > 5.2 = U_t$) wind velocities of the translated Queen Alia Airport weather-data from 1983-2012.

plot dimensions were scaled and drawn on grid paper. The scaled plot was scanned and loaded into a GIS programme and converted into a PcRaster valid (Ascci) format. The data file consisted of 200 cell rows and 140 cell columns and was used as base map for the model (clone.map). The cell dimension was defined at 0.25 m resulting in an experimental area of $50 \times 35\,m$ (figure 4.9). The outer boundary of the experimental area (Purple area) was functioning as Non Erodible Boundary (NEB) (figure: 4.9), the inner area of $45 \times 30\,m$ (Colored area) was the erodible plot. The Barley and Natural grazing plots were both characterized by zero cover, meaning that the entire plot was erodible (figure: 4.10). However the Water harvesting plot consisted of vegetation lines whereby the plot is divided into a vegetation area of 20% of the total area (Red) and an erodible area (Green) of 80% of the total area (figure: 4.11).

4.5.2 Input modules

Three different weather datasets were used for the dynamic weather module: wind velocity, wind direction and temperature. Unfortunately not all

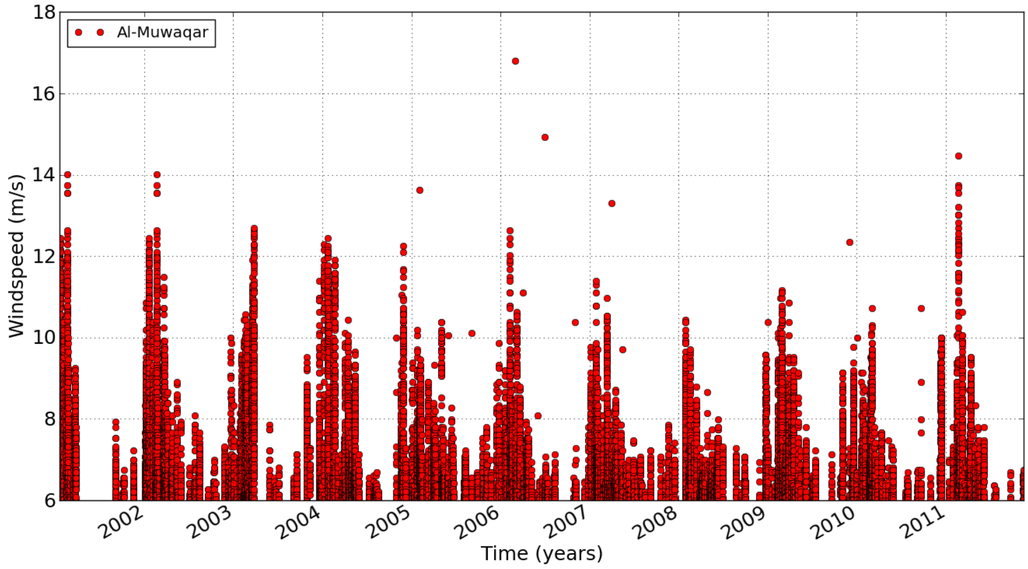

Figure 4.8: Selected ($U_2 > 6.0 = U_t$) wind velocities of the translated Al-Muwaqar weather-data from 2001-2011. Whereby a minimum of six wind velocities per day ($U_2 > U_t$) was required

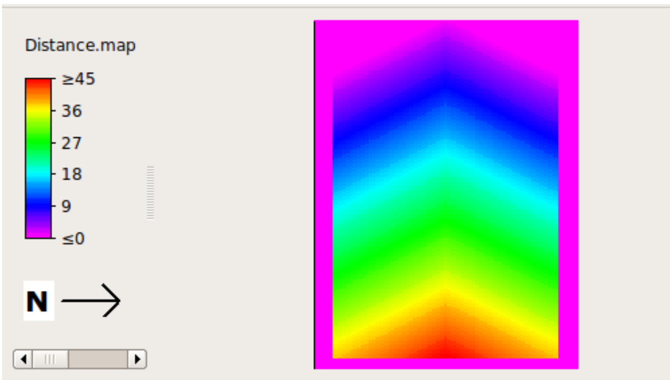

Figure 4.9: Model area with the distance from the Non erodible boundary (purple area) sediment transport goes from West to East direction

model data was available. Each dataset had a correct set of wind velocities. However wind direction were not available for the Queen Alia airport dataset and the wind directions of Al-Muwaqar contained observations er-

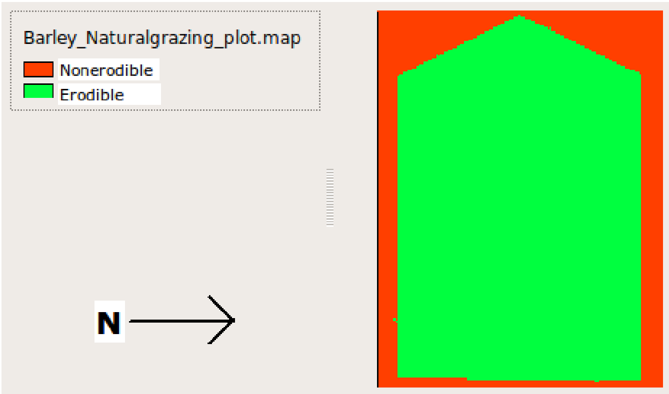

Figure 4.10: Model area of the natural grazing and Barley plot

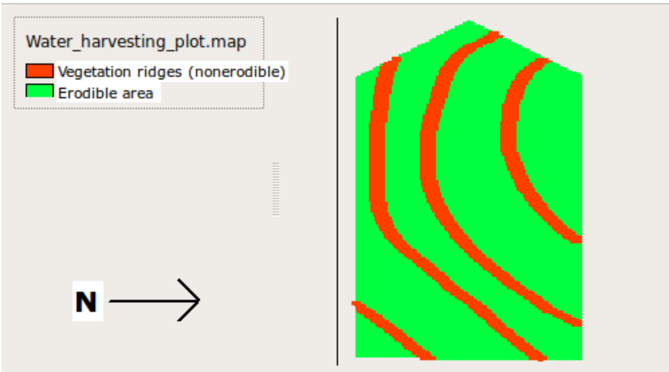

Figure 4.11: Model Areas of the water harvesting plot with *True* a suitable experimental area with 80% cover and *False* vegetation area with 20% cover (percentage are of the total area)

rors. The UU dataset was insufficient for modelling because the wind velocities at Al-Majidyya in 2011 did not exceed the wind velocity threshold ($U_2 < U_t$). Nevertheless the decision was made to run the model with some potential wind erosion seasons from the Al-Muwaqar data. The translated Al-Muwaqar dataset was used (figure: 4.6) in combination with the wind velocity threshold of 6 m/s. This wind velocity threshold was based on equation 4.1 with an averaging time of 10 minutes. Besides the translation of wind velocity also wind direction data was adapted to reduce extreme measurements errors. The RWEQ model used only wind velocities whereby $U_2 > U_t$, otherwise wrong wind factors were calculated. The temperature in C° was converted to Kelvin and used for calculating the air density which in turn was used for the calculation of the weather factor (section 3.8.1).

Other model input data like rainfall,evaporation,irrigation and snow depth were not applicable to the Jordan Badia.

The soil module calculated the Soil Crust Factor (SCF) and the Erodible Fraction (EF), both factors depend on the soil surface properties described in table 3.1. The RWEQ model used Organic matter, Sand, Clay, Silt and Calcium Carbonate soil properties. One set of soil parameters was used for each plot and will not change over time (initial based).

The vegetation module was simplified and used as a cover factor for stones and vegetation. The Combined Crop factor or Crops on Ground (COG) was in the original RWEQ model depending on standing residues and crop/vegetation canopy. On neither of the plots were standing residues like crop or vegetation stalks. Crop canopy was only valid for green leafs and not for shrubs. Therefore it was decided to use 10% flat cover factor for stones/rocks for all three plots. The crop canopy factor on the Water harvesting plot was replaced by a block cover factor representing the shrub height and width in combination with the ridge and furrow dimensions. The block cover factor was calculated as 20% cover (figure: 4.11). The vegetation module was calculated once per model run and did also not change over time (initial based).

The soil ridge roughness factor was only used for the Barley plot whereby the ridge height= 0.15 m, ridge space= 0.60 m and orientation of the ridges = West to East. The single roughness factor (K_{tot}) of the Barley plot was depending on both the soil ridge roughness factor and the random roughness factor. The Natural grazing plot don't had ridges and the roughness elements (vegetation furrows) on the Water harvesting plot were used in the vegetation module. So these plots were only dependent on the random roughness factor. The random roughness factor was set on RR=0.53 (dimensionless) for each plot, based on a visual estimation in the field and compared with some predefined areas of roughness cover described in the RWEQ manual of Fryrear et al. (1998).

4.5.3 Plot results

Four periods were chosen based on their large number of valid wind velocities. This resulted in a wind erosion season from January till March. Note: this decision was only based on two historical wind datasets, because wind erosion depends on several weather factors (wind,precipitation,evaporation and irrigation) and so this might not be the optimal wind erosion season chosen. Table 4.4 shows the RWEQ results of the potential wind erosion periods 2002,2003,2004 and 2011, whereby each period was modeled with a different nr. of timesteps. One timestep was based on 10 minutes.

Table 4.4: RWEQ model results of (wf) Weather factor (W_F), Maximum transport Q_{max} and mass transport $Q(x)$ and soil loss S_L from Jan-March of 2002,2003,2004 and 2011 whereby, PL1=Barley plot,PL2=Water harvesting and PL3=Natural grazing plot

Year *Jan-March*	Timesteps *nr.*	Wind velocity *Mean/Max*	wf *range* $(m/s)^3$	W_F *range* (kg/m)	Q_{max} *range* (kg/m)			$Q(x)$ *range* (kg/m)			S_L *range* (kg/m)		
					PL1	PL2	PL3	PL1	PL2	PL3	PL1	PL2	PL3
2002	1480	7.77/14.02	0-38	0-4.4	0-7.9	0-0.82	0-4.2	0-3.0	0-0.06	0-1.01	0-0.13	0-0.003	0-0.05
$Plot_{average}$	x	x	x	x	x	x	x	0.854	0.017	0.29	0.0614	0.0012	0.021
2003	1368	7.79/13.69	0-34	0-3.9	0-7.0	0-0.73	0-3.75	0-1.98	0-0.04	0-0.67	0-0.09	0-0.002	0-0.03
$Plot_{average}$	x	x	x	x	x	x	x	0.56	0.011	0.2	0.04	0.001	0.014
2004	736	7.88/12.44	0-21.5	0-2.55	0-4.6	0-0.48	0-2.45	0-1.86	0-0.04	0-0.62	0-0.08	0-0.002	0-0.03
$Plot_{average}$	x	x	x	x	x	x	x	0.53	0.01	0.18	0.034	0.0007	0.013
2011	648	7.32/14.46	0-43.5	0-5.05	0-9.0	0-0.94	0-4.85	0-1.46	0-0.03	0-0.49	0-0.065	0-0.001	0-0.02
$Plot_{average}$	x	x	x	x	x	x	x	0.42	0.008	0.14	0.03	0.001	0.01

The Natural grazing plot showed less mass transport $Q(x)$ as expected beforehand, due the differences between the soil factor values. The soil data of the Natural grazing plot gave a lower Erodible factor E_F and Soil Crust factor S_{CF} compared to the barley and Water harvesting plot (table: 4.5). The mass transport values from the Natural grazing plot was for every annual period 2/3 lower compared to the Barley plot who had the largest mass transport and soil losses estimations for each modeled period.

Table 4.5: Initial values for the soil,vegetation and roughness factors.

Plot	*COG* dimensionless	K_{tot} dimensionless	E_F dimensionless	S_{CF} dimensionless
Barley	0.645	0.256	0.40	0.245
Water Harvesting	0.112	0.258	0.39	0.15
Natural grazing	0.645	0.258	0.38	0.14

The ridges (roughness factor) on the Barley plot seems not to have any influence on the K_{tot} factor (table: 4.5) compared to those plots with no ridges. The reason for a similar K_{tot} value was that the orientation of the ridges on the Barley plot were parallel to the wind direction (West) therefore the K_{tot} value was only dependent on the Random roughness factor RR and was the same for each plot. The mass transport $Q(x)$ and total Soil loss

S_L values for each modelled period were the lowest for the water harvesting plot. The vegetation lines on the Water harvesting plot had large influence on the Combined crop factor (COG) respectively 0.11 compared to the other plot values > 0.64 (table: 4.5). This lower COG factor resulted in a 98% lower mass transport for $Q(x)$ compared to the Barley and 94% lower for the Natural grazing plot. Overall the model showed that the Water harvesting plot is less erodible compared to the other two plots.

The length (Jan-March) was similar in duration to the measurement period in Al-Majidyya 2011. The use of four periods made the model more representative, meaning that not only 10 years ago wind erosion was obtained but also at the begin of 2011. All subsets were similar in average wind velocity ($\approx 7.7\, m/s$). However the number of valid timesteps ($U_2 > U_t$) was different for every period (table: 4.4). The period of 2003 had twice more nr. of timesteps compared to the period of 2011. However the mass transport of $Q(x)$ was not doubled, meaning that were wind velocity values in the 2011 period with more continuous high wind velocities. To see which subset generates most wind erosion per time unit, the average results were divided by the number of timesteps. This resulted that the season of 2004 had the highest $Q(x)$ and S_L values per averaged time unit of 10 minutes. The ratios between the $Q(x)$ and S_L values of the different plots remain the same because the time independent values of the Soil,Vegetation and Roughness module were not changed. The choice for a correct wind velocity threshold (U_t) in the RWEQ model was crucial. For this study the threshold was based on soil properties for experimental wind erosion fields in spain [Sterk et al., 1999] and the *time fraction equivalence method* of Stout and Zobeck (1997). The most appropriate method for obtaining a reliable value of the U_t parameter is the use of active wind erosion instruments like SALDECs [Thuy, 2011] or Saltiphones [Spaan and van den Abeele, 1991] what was not possible due the lack of saltation data. The model results are the first initial estimations of the mass transport and soil loss rates for three different agricultural plots. However model calibration parameters were not obtained due to insufficient data. Therefore default calibration parameters were used from field experiments in the USA 2004 [Van Pelt et al., 2004]. Nevertheless the model gave a first result that wind erosion took place for different periods in the past. Wind erosion events are needed in future for obtaining the calibration parameters and verifying the model output values. Additional datasets in combination with better estimation techniques for obtaining soil and cover characteristics are needed to make the model predictions more precise and liable.

Some examples of the spatial distributions of $Q(x)$ and S_L are shown in figure 4.12.

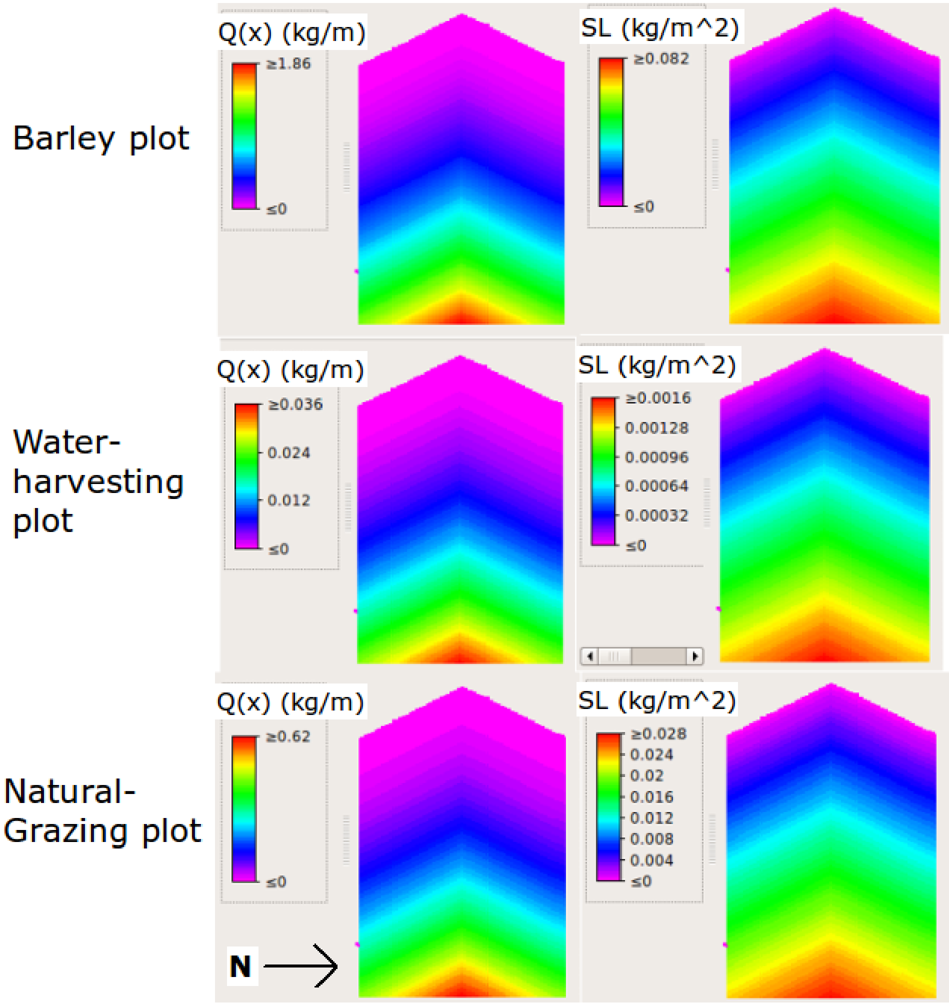

Figure 4.12: Spatial distribution of the predicted Mass transport (kg/m) and Soil loss (kg/m^2) by the model for the Barley plot during a 5 day period (Jan-March) 2004

Chapter 5

Conclusions

This study was the first detailed experimental research of aeolian sediment transport in the Badia of Jordan. Unfortunately there were no storm events recorded by the active and passive wind erosion instruments on any of the three experimental plots during the measurement period June-September 2011 in Al-Majidyya.

Three experimental plots with soil textures of Silt Loam/Clay Loam were studied on their vulnerability for wind erosion. Three weather datasets were obtained: UU, Al-Muwaqar and Queen Alia Airport during the field work in 2011. The UU dataset (1 minute records) showed an average wind velocity of 3.18 m/s, ($\sigma = 0.69\,m/s$) based on daily averages in combination with a West wind direction of 266° ($\sigma = 13°$). The maximum wind velocity during the measurement period was 7.37 m/s. The Al-Muwaqar dataset contained measurements based on 10 minutes. The Queen Alia Airport dataset had records based on daily averages. Both datasets cover period a historical period of 2001-2011 for Al-Muwaqar and 1983-2012 for Queen Alia Airport. The Al-Muwaqar dataset was significant lower in wind velocity compared to the UU datasets, which had an $RMSE$ of 1.23 m/s and an MAE of 1.13 m/s. The wind velocity of Queen Alia Airport was significant higher compared to the UU dataset which had an $RMSE$ of 0.90 m/s and an MAE of 0.56 m/s. The standard deviation of the observation ratios between UU and Al-Muwaqar was 0.13 and 0.17 for the observations between UU and Queen Alia Airport. Both sets had a constant offset from the UU dataset. Unfortunately there was no wind direction data available for the Queen Alia airport station and the wind direction data of the Al-Muwaqar dataset contained measurement/log errors for several days, which should be taking into account.

The aerodynamic roughness parameter z_0 say something about the roughness (m) of a terrain. For the Barley and Natural grazing plot this value was $\approx$ 10 cm, something what meet our expectations. The Barley plot had ridges of 15 cm high however the ridges were parallel with the predominant wind direction and therefore no obstacle for the wind. The Water harvesting plot consisted of ridges and shrubs planted in furrows what covered the plot surface for 20% resulting in a z_0 value of $\approx$ 17 cm.

According to ICARDA and NCARE, the storm season is from June-September [Sterk, 2011]. However the results in this study show a different storm season. For Queen Alia Airport 1215 potential wind erosion days were selected whereby $U_2 > 5.2m/s$ from 1983-2012. From this selection 59% (714 events) falls in the October-March period. Of the 17891 selected ($U_2 > 6.0m/s$) potential wind erosion events of Al-Muwaqar from 2001-2011, 69% (12318 events) falls in the October-March period.

The RWEQ model estimated mass transport and soil loss values for the periods (Jan-March) from 2002,2003,2004 and 2011. These periods were selected from the translated Al-Muwaqar dataset. The period of 2002 and 2003 had the most valid potential wind erosion days (> 9 days) and resulted in a total mass transport range for the Barley plot of $Q(x)_{2002} = 0 - 3.0\ (kg/m)$, $S_{L,2002} = 0 - 0.13\ (kg/m^2)$ and $Q(x)_{2003} = 0 - 2.0\ (kg/m)$, $S_{L,2003} = 0 - 0.09\ (kg/m^2)$. However the 2004 model showed the highest average mass transport and soil loss per 10 minutes and for 5 days there was already a $Q(x)_{2004} = 0 - 1.86\ (kg/m)$, $S_{L,2004} = 0 - 0.08\ (kg/m^2)$. The period of 2011 showed that wind erosion took place recently. The periods of 2005 and 2006 were not modeled but showed some potential wind erosion days as well. It is concluded that wind erosion was occurred for different periods during the last ten years. The vulnerability of the soils for wind erosion were different for each plot. The highest mass transport and soil losses were obtained for the Barley and Natural grazing plot. However the Natural grazing plot is 2/3 less compared to the Barley plot. The Water harvesting plot showed almost no wind erosion. The mass transport and soil losses were for the Water harvesting with > 90% reduced compared to the quantities of the Barley and Natural grazing plot. The reason for this significant lower obtained wind erosion quantities were due the different obtained cover and soil properties of the three plots. The Soil Crust and Erodible factor of the soil module were lower for the Natural grazing plot (table: 4.5). The Combined Crop factor in the vegetation module was only different (0.11 vs. 0.645) for the Water harvesting plot due to the presence of vegetation lines where shrubs were planted in furrows. The ridges on the Barley plot had almost no influence on the single roughness factor (roughness module) and was therefore the same for each plot (0.26). Default RWEQ calibration parameters were used in this model. Individual wind erosion events are needed in future for obtaining the calibration parameters and verifying the model output values. .

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Appendix A

A.1 Saldec registrations (June-Sept) 2011

Table A.1. SALDEC registrations from 29 June till 18 September 2011, whereby U(2) > 7 m/s

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
SALDEC 1 registrations are:			
2011-06-29	13:15:00	0.0	7.35
2011-06-29	16:34:00	0.0	7.04
2011-06-29	16:59:00	0.0	7.04
2011-06-29	17:38:00	0.0	7.03
2011-06-29	17:43:00	0.0	7.19
2011-06-29	17:44:00	0.0	7.07
2011-06-29	18:16:00	0.0	7.11
2011-06-30	07:46:00	0.0	7.05
2011-06-30	07:47:00	0.0	7.15
2011-06-30	10:25:00	0.0	7.01
2011-06-30	11:38:00	0.0	7.16
2011-06-30	12:32:00	0.0	7.08
2011-06-30	13:22:00	0.0	7.23
2011-06-30	13:32:00	0.0	7.11
2011-06-30	14:08:00	0.0	7.03
2011-06-30	16:11:00	0.0	7.23
2011-06-30	17:18:00	0.0	7.13
2011-06-30	17:26:00	0.0	7.13
2011-06-30	17:27:00	0.0	7.15
2011-06-30	17:35:00	0.0	7.05
2011-06-30	18:36:00	0.0	7.0
2011-07-03	16:50:00	0.0	7.32
2011-07-08	16:57:00	0.0	7.11
2011-07-08	17:11:00	0.0	7.37
2011-07-08	17:19:00	0.0	7.12
2011-07-08	17:21:00	0.0	7.29
2011-07-10	14:21:00	0.0	7.03
2011-07-10	14:35:00	0.0	7.23
2011-07-10	14:58:00	0.0	7.0
2011-07-10	15:06:00	0.0	7.04
2011-07-10	15:29:00	0.0	7.05
2011-07-10	15:33:00	0.0	7.04
2011-07-10	15:34:00	0.0	7.35
2011-07-10	15:47:00	0.0	7.03

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
2011-07-10	16:21:00	0.0	7.15
2011-07-10	16:36:00	0.0	7.2
2011-07-10	16:50:00	0.0	7.09
2011-07-10	17:00:00	0.0	7.08
2011-07-10	17:01:00	0.0	7.23
2011-07-10	18:08:00	0.0	7.09
2011-07-11	11:21:00	0.0	7.07
2011-07-11	12:09:00	0.0	7.15
2011-07-11	12:10:00	0.0	7.0
2011-07-11	12:24:00	0.0	7.12
2011-07-11	12:41:00	0.0	7.28
2011-07-11	12:50:00	0.0	7.07
2011-07-11	13:05:00	0.0	7.04
2011-07-11	13:10:00	0.0	7.11
2011-07-11	13:11:00	0.0	7.09
2011-07-11	14:46:00	0.0	7.17
2011-07-11	15:14:00	0.0	7.15
2011-07-11	15:42:00	0.0	7.16
2011-07-11	15:44:00	0.0	7.01
2011-07-11	16:48:00	0.0	7.17
2011-07-11	16:54:00	0.0	7.03
2011-07-11	17:04:00	0.0	7.27
2011-07-11	17:05:00	0.0	7.03
2011-07-11	18:13:00	0.0	7.08
2011-07-17	12:33:00	0.0	7.08
2011-07-17	16:26:00	0.0	7.13
2011-07-18	09:24:00	0.0	7.04
2011-07-18	11:55:00	0.0	7.09
2011-07-18	15:25:00	0.0	7.13
2011-07-19	15:16:00	0.0	7.01
2011-07-20	14:21:00	0.0	7.04
2011-07-23	19:24:00	0.0	7.0
2011-07-28	14:49:00	0.0	7.0
2011-07-28	15:03:00	0.0	7.13
2011-08-03	15:20:00	0.0	7.05
2011-09-04	15:45:00	0.0	7.04
2011-09-12	15:19:00	0.0	7.33

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)

SALDEC 2 registrations are:

2011-06-29	13:15:00	0.0	7.35
2011-06-29	16:34:00	0.0	7.04
2011-06-29	16:59:00	0.0	7.04
2011-06-29	17:38:00	0.0	7.03
2011-06-29	17:43:00	0.0	7.19
2011-06-29	17:44:00	0.0	7.07
2011-06-29	18:16:00	0.0	7.11
2011-06-30	07:46:00	0.0	7.05
2011-06-30	07:47:00	0.0	7.15
2011-06-30	10:25:00	0.0	7.01
2011-06-30	11:38:00	0.0	7.16
2011-06-30	12:32:00	0.0	7.08
2011-06-30	13:22:00	0.0	7.23
2011-06-30	13:32:00	0.0	7.11
2011-06-30	14:08:00	0.0	7.03
2011-06-30	16:11:00	0.0	7.23
2011-06-30	17:18:00	0.0	7.13
2011-06-30	17:26:00	0.0	7.13
2011-06-30	17:27:00	0.0	7.15
2011-06-30	17:35:00	0.0	7.05
2011-06-30	18:36:00	0.0	7.0
2011-07-03	16:50:00	0.0	7.32
2011-07-08	16:57:00	0.0	7.11
2011-07-08	17:11:00	0.0	7.37
2011-07-08	17:19:00	0.0	7.12
2011-07-08	17:21:00	0.0	7.29
2011-07-10	14:21:00	0.0	7.03
2011-07-10	14:35:00	0.0	7.23
2011-07-10	14:58:00	0.0	7.0
2011-07-10	15:06:00	0.0	7.04
2011-07-10	15:29:00	0.0	7.05

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
2011-07-10	15:33:00	0.0	7.04
2011-07-10	15:34:00	0.0	7.35
2011-07-10	15:47:00	0.0	7.03
2011-07-10	16:21:00	0.0	7.15
2011-07-10	16:36:00	0.0	7.2
2011-07-10	16:50:00	0.0	7.09
2011-07-10	17:00:00	0.0	7.08
2011-07-10	17:01:00	0.0	7.23
2011-07-10	18:08:00	0.0	7.09
2011-07-11	11:21:00	0.0	7.07
2011-07-11	12:09:00	0.0	7.15
2011-07-11	12:10:00	0.0	7.0
2011-07-11	12:24:00	0.0	7.12
2011-07-11	12:41:00	0.0	7.28
2011-07-11	12:50:00	0.0	7.07
2011-07-11	13:05:00	0.0	7.04
2011-07-11	13:10:00	0.0	7.11
2011-07-11	13:11:00	0.0	7.09
2011-07-11	14:46:00	0.0	7.17
2011-07-11	15:14:00	0.0	7.15
2011-07-11	15:42:00	0.0	7.16
2011-07-11	15:44:00	0.0	7.01
2011-07-11	16:48:00	0.0	7.17
2011-07-11	16:54:00	0.0	7.03
2011-07-11	17:04:00	0.0	7.27
2011-07-11	17:05:00	0.0	7.03
2011-07-11	18:13:00	0.0	7.08
2011-07-17	12:33:00	0.0	7.08
2011-07-17	16:26:00	0.0	7.13
2011-07-18	09:24:00	0.0	7.04
2011-07-18	11:55:00	0.0	7.09
2011-07-18	15:25:00	0.0	7.13
2011-07-19	15:16:00	0.0	7.01
2011-07-20	14:21:00	0.0	7.04
2011-07-23	19:24:00	0.0	7.0
2011-07-28	14:49:00	0.0	7.0
2011-07-28	15:03:00	0.0	7.13

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
2011-08-03	15:20:00	0.0	7.05
2011-09-04	15:45:00	0.0	7.04
2011-09-12	15:19:00	0.0	7.33

SALDEC 3 registrations are:

2011-06-29	13:15:00	0.0	7.35
2011-06-29	16:34:00	0.0	7.04
2011-06-29	16:59:00	0.0	7.04
2011-06-29	17:38:00	0.0	7.03
2011-06-29	17:43:00	55.0	7.19
2011-06-29	17:44:00	54.0	7.07
2011-06-29	18:16:00	0.0	7.11
2011-06-30	07:46:00	0.0	7.05
2011-06-30	07:47:00	0.0	7.15
2011-06-30	10:25:00	0.0	7.01
2011-06-30	11:38:00	0.0	7.16
2011-06-30	12:32:00	0.0	7.08
2011-06-30	13:22:00	0.0	7.23
2011-06-30	13:32:00	0.0	7.11
2011-06-30	14:08:00	0.0	7.03
2011-06-30	16:11:00	0.0	7.23
2011-06-30	17:18:00	0.0	7.13
2011-06-30	17:26:00	0.0	7.13
2011-06-30	17:27:00	0.0	7.15
2011-06-30	17:35:00	0.0	7.05
2011-06-30	18:36:00	0.0	7.0
2011-07-03	16:50:00	0.0	7.32
2011-07-08	16:57:00	0.0	7.11
2011-07-08	17:11:00	0.0	7.37
2011-07-08	17:19:00	0.0	7.12
2011-07-08	17:21:00	0.0	7.29
2011-07-10	14:21:00	0.0	7.03
2011-07-10	14:35:00	0.0	7.23

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
2011-07-10	14:58:00	0.0	7.0
2011-07-10	15:06:00	0.0	7.04
2011-07-10	15:29:00	0.0	7.05
2011-07-10	15:33:00	0.0	7.04
2011-07-10	15:34:00	0.0	7.35
2011-07-10	15:47:00	0.0	7.03
2011-07-10	16:21:00	0.0	7.15
2011-07-10	16:36:00	0.0	7.2
2011-07-10	16:50:00	0.0	7.09
2011-07-10	17:00:00	0.0	7.08
2011-07-10	17:01:00	0.0	7.23
2011-07-10	18:08:00	0.0	7.09
2011-07-11	11:21:00	0.0	7.07
2011-07-11	12:09:00	0.0	7.15
2011-07-11	12:10:00	0.0	7.0
2011-07-11	12:24:00	0.0	7.12
2011-07-11	12:41:00	0.0	7.28
2011-07-11	12:50:00	0.0	7.07
2011-07-11	13:05:00	0.0	7.04
2011-07-11	13:10:00	0.0	7.11
2011-07-11	13:11:00	0.0	7.09
2011-07-11	14:46:00	0.0	7.17
2011-07-11	15:14:00	0.0	7.15
2011-07-11	15:42:00	0.0	7.16
2011-07-11	15:44:00	0.0	7.01
2011-07-11	16:48:00	0.0	7.17
2011-07-11	16:54:00	0.0	7.03
2011-07-11	17:04:00	0.0	7.27
2011-07-11	17:05:00	0.0	7.03
2011-07-11	18:13:00	0.0	7.08
2011-07-17	12:33:00	0.0	7.08
2011-07-17	16:26:00	0.0	7.13
2011-07-18	09:24:00	0.0	7.04
2011-07-18	11:55:00	0.0	7.09
2011-07-18	15:25:00	0.0	7.13
2011-07-19	15:16:00	0.0	7.01
2011-07-20	14:21:00	0.0	7.04

Table A.1—Continued

Date (YYYY−MM−DD)	Time (HH:MM)	Saldec Count (p/m)	wind velocity (m/s)
2011-07-23	19:24:00	0.0	7.0
2011-07-28	14:49:00	0.0	7.0
2011-07-28	15:03:00	0.0	7.13
2011-08-03	15:20:00	0.0	7.05
2011-09-04	15:45:00	0.0	7.04
2011-09-12	15:19:00	0.0	7.33