Sheffield Hallam University

Faculty of Development and Society

Application of Geographical Information Systems and Remote Sensing in Estimating the Likely Breeding and Infested areas of the Desert Locust (*Schistocerca gregaria,* Forskal)

By

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A **thesis submitted to Sheffield Hallam University for the partial fulfillment of the requirement of M. Sc degree in Geographical Information Systems**

January 2011

Word count: 16413

Student number: 19039281

Acknowledgments

I would like to express my sincere thanks to:

-Andrew Jones, my supervisor, for his feedback, advice and support during the preparation of this study.

- The Food and Agriculture Organization - Commission for controlling the desert locust in the Central Region (FAO-CRC), for funding the study and living expenses in UK.

- Dr Munir Butros, the FAO-CRC general secretary for his continuous support, advice and for recommending me to study this master degree in UK.

- Keith Cressman, FAO-UN, Rome, for his help and providing some studying materials for the work.

- Mr Mohammed AbdolRahman, the general manager of the locust headquarter of the ministry of Agriculture of Egypt and Mr Fatthi Mahfouz my direct manager in Qena Locust Unit, for their continuous help and support before and during the study. Also my thanks are due to Mr Ahmed Kamel, Mr Ragab Bakry and to my work colleagues: Tamer AbdelHameed , Emad Kameel and Atef Saleem, the people who encouraged and supported me.

- Special thanks to my work colleagues: Osama Taha, Essam Mahmoud, Ahmed Ismaeil and Mohammed Reyad, for their help and for providing the data required for the work.

Abstract

The study presents two methods for identifying and estimating the areas predicted to have infestations and breeding by the desert locust. The first makes use of the applications of Geographical Information Systems (GIS) and remote sensing techniques, and the second utilizes geostatistical analysis using the kriging interpolation for predicting the infestations in the sites un-surveyed by survey teams. The spatial dependency of the desert locust infestations was also measured. It was found that infestations by the desert locust in the study area mainly occurred within the vegetation cover which has an Enhanced Vegetation Index (EVI) value of > 0.05 to 0.2, and this was utilized to identify the size and extent of the green vegetation in which infestations and breeding mainly occur. In addition, kriging proved to be a good model for predicting the size of infestations under specific conditions. However, this was not true for all cases as it did not show good performance in certain situations. Additionally, the infestations by the desert locust were found to be spatially dependent on a range of 0.082 to 0.29 decimal degrees.

Preface

The study includes five chapters, which demonstrate the stages of the work. Each chapter contains specific details related to the work progress as illustrated below:

Chapter one: Introduction

This chapter presents a short introduction about the desert locust, its recession area and economic problems. In addition, it provides information on the preventive control strategy and the forecast of the desert locust situation, which is used to avoid the danger this pest inflicts on crops and pastures consumed by mankind. Moreover, the chapter highlights the specific focus and the scope of the study; it states the research questions, the study aim and the objectives.

Chapter two: literature review

This chapter overviews the most important literature related to the desert locust. This covers the desert locust life cycle, the effect of the ecological conditions on the desert locust, the outbreaks and recessions periods of the desert locust. Then it clarifies the procedures applied to carry out the survey operations that monitor the desert locust and its habitat.

The other sections of the literature review overview the previous studies of the GIS and remote sensing techniques and their applications in the management of the desert locust. This includes their use in forecasting the situation of the desert locust, in investigating the ecological conditions that affect the pest and in estimating the green vegetation areas.

Chapter three: Methodology and data analysis

This chapter outlines the study design, the study area, the data types and sources. Additionally, it indicates the GIS analysis of the survey data and remote sensing imagery data, which were used to achieve the aim and objectives of the study.

Chapter four: Results and discussions

This chapter provides the results of the analysis and the possible interpretations of these results based on the context of the previous applications and studies. In addition, a summary for the results is provided for the long sections.

Chapter five: General discussions, conclusion and recommendations

This chapter presents and discusses the main findings of the research study. It outlines the contribution the study could make to the body of knowledge in the desert locust management.

The conclusion illustrates how the findings of the study could be empirically implemented. The recommendations highlight some suggestions for implementing the findings of this study and, propose some future studies that can improve our understanding and the procedures of coping with this pest. Finally, the general limitations of the current study are pointed out.

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Chapter One: Introduction

1.1. General Overview

The researcher has selected this study as a topic for his thesis since he himself has worked in the Locust Control Department in Egypt. The study can improve the performance of the survey operations by identifying the suitable breeding habitat, and the predictable areas of infestation inflicted by the desert locust in the areas monitored by survey teams during the periods of increased locust activity.

The desert locust (*Schistocerca gregaria* Forskal) is a large grasshopper belonging to the Orthoptera family of the insect class. It lives in the arid and semi-arid desert habitat, extending from the north equator in Africa, the Red Sea coasts and the near East, to south west Asia. This vast area is called the recession area; it doubles during plagues from 16 million square kilometres to around 29 million square kilometres, as can be seen in Figure (1) (Showler, no date). The Red Sea coastal plains of Africa and the Arabian Peninsula are important breeding areas for the desert locust; this region has been implicated as a source of transit areas for desert locust swarms which threaten agriculture. The desert locust can live in two or more phases (Uvarov, 1977); they are the solitary and gregarious phases, with an intermediate form called the transient phase. The differences between them are manifested in behaviour and external colour. Solitary insects live at low densities and do not cause threats to the crops and pastures, but they can congregate if successful breeding occurs. Successful breeding is due to favourable ecological conditions which occur as a result of widespread rainfall with the subsequent growth of vegetation cover; the locusts form hopper bands and swarms (Hielkema, Roffey and Tucker, 1985). The swarms of desert locusts are devastating; they cause the greatest damage to crops and pastures during the periods of increased locust activity. A medium-sized swarm may contain a thousand million locusts and cover an area of 20 square kilometres. Such a swarm will consume some 3000 tonnes of vegetation per day, and this can lead to starvations in the worst conditions. In addition, the hopper bands of gregarious desert locusts feed on the green vegetation in the areas where they live. The desert locust was described by Van Huis (2007) as a political pest, because its damage during plagues demands a popular action, and the swarm migration for great distances makes it a transitional problem; consequently, it receives much attention from the press and subsequently from the politicians.

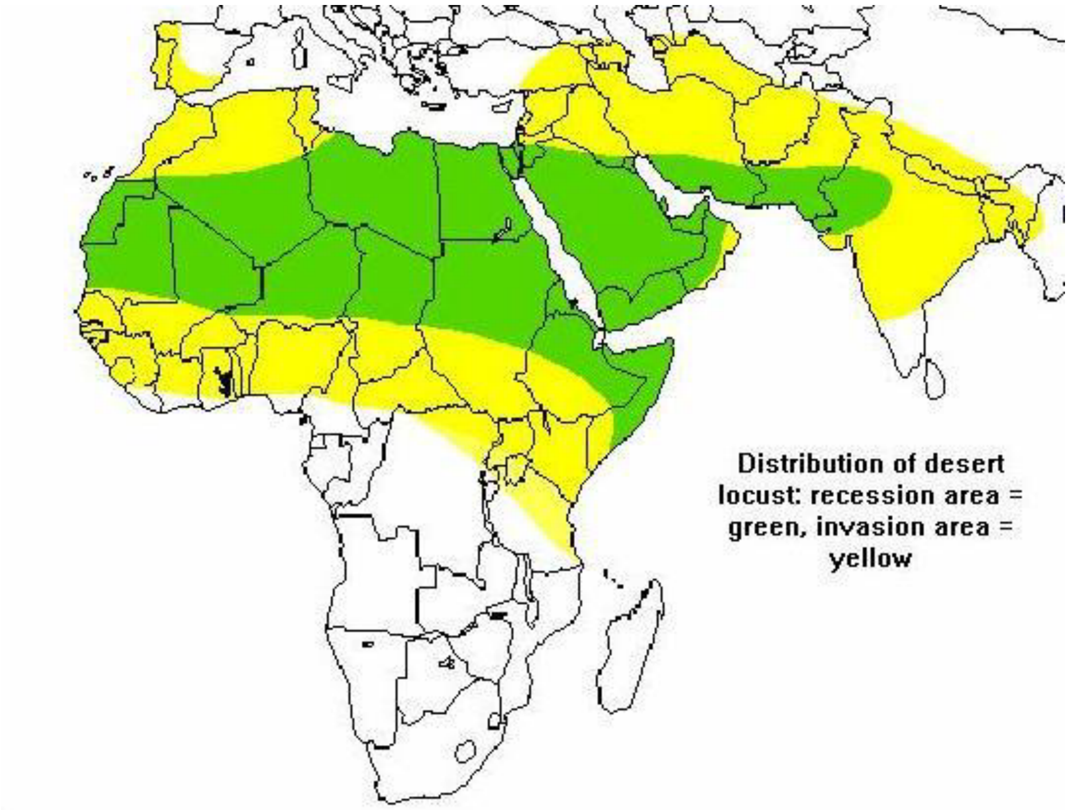


Figure1: Recession and invasion areas of the desert locust

(Showler, no date)

The recession area affected by the desert locust is divided by the Food and Agriculture Organisation (FAO) into three regions: western, central and eastern. The western region includes countries located in Africa including Algeria, Chad, Libya, Mali, Mauritania, Morocco, Niger, Senegal and Tunisia. The central region includes countries along the Red Sea: Djibouti, Egypt, Sudan, Somali, Ethiopia, Saudi Arabia, Oman, Eritrea and Yemen. Finally, the eastern region includes the south west Asian countries of Iran, Pakistan, India and Afghanistan (FAO, 2004a).

1.2. The Preventive Control Strategy of the Desert Locust

From the previous overview, it can be concluded that there is a need for the preventive control strategy to stop the danger and threats of this pest to crops and pastures, especially as it breeds in areas which are in great need for food and their food resources are limited. The aim of the preventive control strategy against the desert locust is to prevent the development of the breeding and formation of hopper bands and swarms (Cressman, 1996a, b). The strategy involves the control of both the locust populations during upsurges in order to prevent them from spreading to the agricultural areas, and the congregating populations to reduce the amounts of insecticides needed for controlling them and decreasing the extent of the sprayed areas (Rosenberg, 2000). This requires regular monitoring of locust breeding areas and the ability to mount quick small scale control operations to halt its growth into large swarms and hopper bands. Currently, the countries affected by the desert locust maintain regular survey programmes for monitoring this pest and its habitat.

The survey operations are conducted in the suitable breeding habitat, and control operations are implemented if locusts were found in high gregarious densities, to diminish its danger to crops and pastures in the infested and neighbouring areas. During surveys, data are collected about the desert locust and the environment, and other data about previous control operations. These data are sent to the headquarters of locust control in each affected country. The survey results which are obtained from the countries of the recession areas are used side by side with the remote sensing imagery data of green vegetation and rainfall, together with the meteorological data of the wind and temperature, in order to make forecasts about the desert locust situation in the forthcoming period. These forecasts are parts of the preventive control strategy, as they help countries to react according to the expected events. The forecasts of the desert locust were produced originally at the anti-locust research centre in London, and now they are prepared by the Desert Locust Information Services (DLIS) in FAO in Rome. There are two types of forecasts: long term forecasts to help officials to allocate budgets to regional and national locust organizations, and medium or short term forecasts to guide the people responsible for the seasonal and daily deployment of survey and control teams (Magor, 1995).

The DLIS prepares a monthly desert locust bulletin at the beginning of every month for the affected countries in the recession area. This bulletin contains a summary of the locust activity, weather and ecological conditions during the previous month, and the expected future developments in the desert locust situation in the following month/months (Cressman, 1996a). In addition, the local locust information departments in the countries affected by the desert locust use the survey data to enter into a custom GIS program provided by FAO, in order to plan the surveys on the national level according to the need of each country.

1.3. The Specific Focus of This Study

The infestation and breeding of the desert locust occur in large areas within the recession area. Infestation occurs as swarms or individual insects migrate to an area (infested areas), while breeding occurs as egg fields (sandy areas containing groups of locust eggs), individual hoppers or hopper bands in an area (breeding areas). Cressman, (1996b) defined the infested area as the green vegetation area in which locusts are present. Therefore, the estimation of the green areas prone to invasion or infestation by *Shistocerca gregaria* can represent the likely infested area, and also can represent the likely breeding area where the eggs are laid and hatched after rainfall occurrence.

Normally, the infested areas are estimated at the survey sites by the survey operators after the occurrence of an infestation, but the problem lies in locating these infested areas, especially that the surveyors should cover vast areas, in particular those found in remote and /or inaccessible desert areas. The prior estimation of the likely infested and breeding areas and the determination of their extent can help targeting the survey teams to them directly, in order to avoid wasting time in surveying the non-likely infested and breeding areas. Consequently, this measure can improve the survey performance and save time and efforts for the survey teams to conduct further survey in order to cover larger areas. This can also increase the chances of finding most of the infestations.

The proposed measure can be implemented by applying two methods: the first uses the GIS applications and remote sensing imagery of the green vegetation, rainfall and elevation, in order to estimate and identify the extent of the green areas prone to infestations and breeding. While the second method uses the GIS applications for estimating the predicted infestation areas in the un-surveyed sites. As the survey teams cannot cover the whole recession areas.

1.4. The Scope of the Study

The study investigates the effect of rainfall, green vegetation and the elevation level on the breeding and infestations of the desert locust, using survey data, GIS and remote sensing techniques. It also aims to find out the suitable method of identifying and estimating the likely breeding and infested areas of the desert locust using the GIS and remote sensing imagery. The use of remote sensing images provides the only means, by which the vast recession areas can be monitored.

1.5. Research Hypothesis and Questions

It is hypothesized that there is a spatial autocorrelation between the desert locust infestations and the environmental conditions prevailing in specific areas. The study questions are:

- Do the infestations of the desert locust occur under the occurrence of rainfall, in green vegetation and/or at a specific elevation level?
- Can the infested areas and the likely breeding areas be estimated in advance, prior to an expected invasion or infestation of desert locust swarms to an area?
- Can the infestations of the desert locust in an area be predicted by using survey data provided about the infested areas in the neighbouring locations?

1.6. Aim and Objectives of the Study

The aim of the study is to use the GIS and remote sensing techniques to improve the efficiency of the survey and control operation, and to investigate the spatial autocorrelation of the desert locust with the environmental conditions. The aim can be achieved by these objectives: 1) investigating the effect of rainfall, green vegetation condition and the elevation level on the desert locust infestations and breeding; 2) identifying the most suitable survey targets for the survey teams, by estimating the size and extent of the green vegetation cover in a specific area using the satellite remote sensing images, and; 3) specifying a suitable method to estimate the predicted infested area in the un-surveyed sites to provide useful information for the survey and control operators concerning the sizes and extent of the desert locust infestations. This can improve the results of the survey operations, as the hot spots of infestations can be found by the prediction.

Chapter Two: Literature Review

2.1. Life Cycle of the Desert Locust

The desert locust has an incomplete metamorphosis and its life cycle involves egg, hopper and adult stages. It starts with the egg laying by females after copulation between adult mature male and female; the eggs are laid in groups called egg pods containing 80 to 120 eggs each in sandy soils with green vegetation. The females probe the soil by its rear to lay eggs 5 to 10 centimetres below the soil surface in a bare fine sandy soil with suitable moisture content (Uvarov, 1977). The green vegetation is the source of food for hoppers after hatching. The eggs hatch after a period of 10 to 65 days, depending on the soil moisture contents which help in egg hatching, and on the temperature which helps in the development of eggs. The eggs hatch into first hopper instars, which are converted to the second instars after seven days by the moulting process (changing the old cuticle with a new one). Then, the conversion continues the third and fourth instars, until the fifth instars in case of the gregarious phase hoppers, and until the six instars in the solitary form hoppers (Symmons and Cressman, 2001).

The hopper stage durations take around 35 days from the first to the last instars. The last moulting produces a fledged adult insect with soft wings called fledglings; the wings harden and the adult insects start short flying, then they perform long flying. These adults are sexually immature at first and they mature sexually after migration under the availability of favourable conditions (Symmons and Cressman, 2001). Then, they repeat the life cycle again in the same or another area within the seasonal breeding areas during the winter, spring and summer breeding seasons, which can be seen in Figure 2 by FAO (2004b). The migration of the desert locust is the character which makes it a devastating pest, as the migration of swarms to the un-infested areas without previous warning can cause rapid damage to crops and pastures in these areas (Magor, Lecoq and Hunter, 2008).

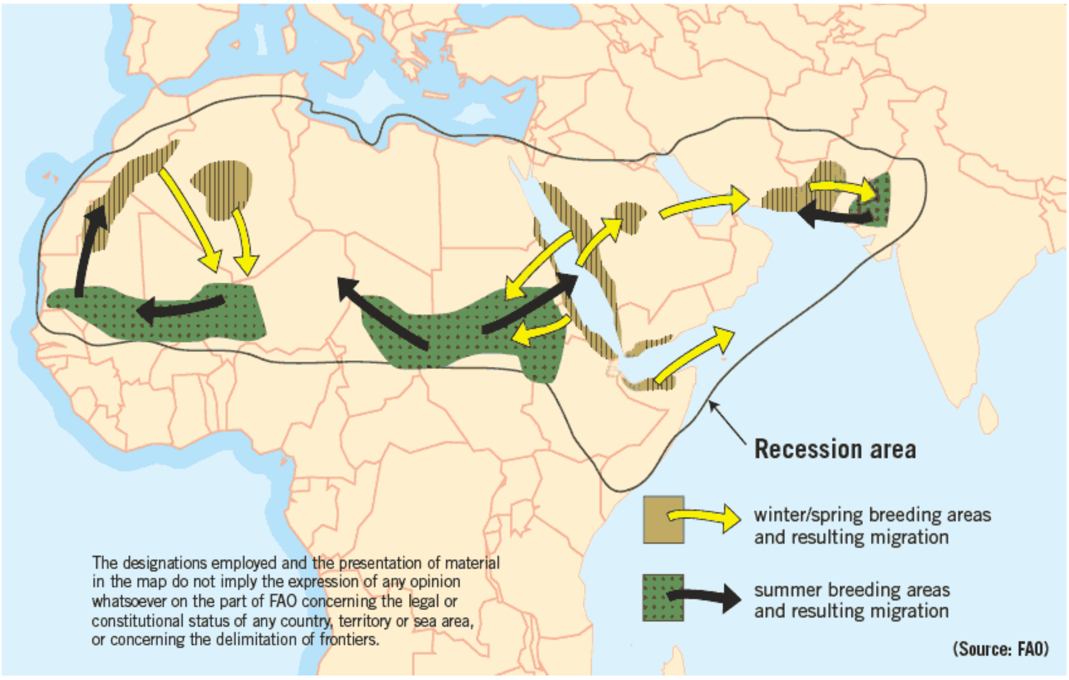


Figure 2: Seasonal breeding areas and migration of the desert locust across the recession area
(FAO, 2004b)

Locust migrates between seasonal breeding areas in the recession area between the breeding seasons (the brown sites represent the winter and spring breeding seasons; the summer breeding areas are coloured with green)

2.2. The Effect of Ecological Conditions on the Desert Locust

The desert locust is a highly mobile insect (Uvarov, 1977), and it has a great capability to respond to favourable environmental conditions (van Huis, 1997). The ecological conditions affecting desert locust breeding and infestations include rainfall, vegetation cover, soil type, wind, temperature and relative humidity. The rainfall provides the necessary water for the growth of green vegetation growth, and the suitable soil moisture for locust breeding, and, egg development and hatching (Hielkema, Roffey and Tucker, 1986; Skaf, Popov and Roffey, 1990). The rainfall is also the main factor which determines the richness and type of vegetation (EL-Sharkawi, et al., 1982). In addition, White (1976) stated that the outbreak of the desert locust occurs after the heavy and widespread rainfall, as it support the vegetation growth for feeding hoppers and adults. Therefore, the widespread rainfall leads to rapid increase in the locust populations, especially in areas where the run-off concentrates the water in specific areas (Waloff, 1966). However, the outbreaks rarely occur as a result of the seasonal rainfall which is rarely heavy, widespread or prolonged to allow the occurrence of outbreaks (Magor, Lecoq and Hunter, 2008).

The green vegetation cover is the other most important factor for the desert locust breeding and infestations, as it is the food source for the locust hoppers and adults. Vegetation also provides shelter for the locust insects from high or very low temperature (Symmons and Cressman, 2001). The soil type also has another effect; as the desert locust breeds only in the sandy soils with suitable soil moisture in the upper 12 centimetres, which permits the females of the desert locusts to lay the eggs (Cherlet, 1993). Moreover, the winds affect locust migration, as locusts migrate downwind to horizontal wind convergence and rainfall (Rainy, 1951; Ibrahim, Sourrouille and Hewitt, 2000). The desert locust swarms migrate to other countries with wind for hundreds of kilometres per day (Farrow, 1990; Symmons, 1992).

The temperature affects the incubation period of eggs, the development of hoppers and adults, and their activity**.** Additionally, the light affects the locust activity as gregarious locust adults migrate during the day in contrast to solitary adults that migrate at night, while hoppers of both forms start their activity during the day and roast at night (Symmons and Cressman, 2001). The effect of temperature, humidity and light is difficult to separate as they have a shared effect on locusts (Uvarov, 1977).

2.3. Recession, Outbreaks, Upsurges and Plagues of the Desert Locust

The plagues of the desert locust can range from Morocco to Pakistan, and their impact on pasture and agriculture is devastating; the locust outbreaks do not follow cyclical patterns, but rather they depend on the weather conditions (Waloff, 1966). The development of a plague situation starts with the recession period, which is characterised by the absence or the limited presence of gregarious populations of locusts. During the recession times, the desert locust populations are found in very low densities (Hemming, et al., 1979). The recessions are punctured by outbreaks which are characterised by increase in the population densities; this is accompanied by a congregation, which may result in the formation of hopper bands and swarms. The outbreaks can lead to plague upsurges when the populations increase and congregate on a larger scale over several generations (Waloff, 1966; Symmons, 1992).

Three concomitant phenomena are distinguished in the generation of locust swarms: concentration, multiplication and gregarization. The concentration occurs as adults migrate toward suitable habitats; the multiplication involves reproduction and population growth, whereas gregarization is a process whereby the locusts form the cohesive group congregate (Roffey and Popov, 1968). From antiquity till the 20th century, some outbreaks developed into wide-spread plagues in 1926-1933, 1941-1947, 1968 and 1987-1989; they have resulted in enormous agricultural losses (Waloff, 1966; Cressman, 1997).

The outstanding feature of plague upsurge, as has been concluded by Hemming, et al., (1979) is the repeated occurrence of widespread and heavy rainfall at appropriate intervals for the successive breeding of locust by several successive generations in connected areas. The resultant building up of containment gregarization (congregation) of locust populations culminates in the production of large numbers of dense swarms. The last stage is the plague period, during which many countries are infested by the successive generations of gregarious locusts, and the simultaneous invasion of locust swarms to many countries; these plagues alternate with recessions (Waloff, 1966; Symmons, 1992). The plagues end as a result of the control operations and the unavailability of favourable environmental conditions, which can lead to dissociating the populations of the desert locust and the return to the low densities.

2.4. The Survey Operation

The strategy of desert locust control is to prevent the formation of hopper bands and swarms (Cressman, 1996a, b). This requires regular surveys in locust breeding areas and the ability to mount quick small scale control operations. The surveys are essential parts of the preventive control strategy, which was first adopted in the 1960s to prevent the occurrence and development of outbreaks, upsurges and plagues of the desert locust (Magor, Lecoq and Hunter, 2008). Therefore, any rational plague prevention strategy must be aimed primarily at mounting regular and frequent surveys in the seasonal breeding areas. This is to ensure the timely detection of any large populations, whether or not they include concentrations dense enough to be called hopper bands or swarms, as upsurges can result from the successful breeding of several successive generations of initially non swarming populations (Roffey, Popov and Hemming, 1970, Hemming, et al., 1979).

The survey operations are conducted in the beginning, mid and end of the rainy seasons, in a favourable habitat for the desert locust, in order to prevent the occurrence of outbreaks, upsurges or plagues of the desert locust. The desert locust surveys involve assessment survey for the identification of green vegetation or habitat with recent rainfall and checking whether the area is infested with locusts, and search survey for finding most locust infestations. The surveys serve many purposes including collecting data about locust infestations, environmental conditions in the area, and information on the locust infestations. The surveys also define the infestation targets to be the controlled. Survey types can be aerial or ground, the aerial survey is conducted by aircrafts or by using the satellites imagery to identify the green vegetation areas, in order to define the potential survey targets, which can be monitored by the ground survey teams (Cressman, 2001).

The survey teams provide the suitable information for forecasting. The survey data were transmitted daily by radio to the national and regional headquarters where they were used to plan the control operations and to conduct them (Healey, et al., 1996). Now, these data can be sent indirectly by radio, fax, and/or e-mail or directly from the field by an electronic device called e-locust2, which is used to record and send the survey data via satellites.

2.5. The Use of GIS in Forecasting the Locust Situation

The early work by Uvarov in the 1930s for mapping the field reports of the locust life-cycle stages established the importance of the temporal and spatial aspects of migrant pests especially the desert locust (Uvarov and Milnthoerpe, 1937). At that time, the forecasts were made by mapping the monthly survey data manually in order to visualize the geographical relationship of the near contemporary reports and their change over time (Healey, et al., 1996). Currently, the DLIS at FAO uses a custom GIS program called SWARMS (Shistocera WARning Management System) consisting of an oracle database, which withholds the received survey data from the affected countries, the meteorological data and the historical records which date back to 1930s, and ESRI's ArcGIS software for querying, displaying and analyzing the data. The system integrates survey data with the meteorological data and the remote sensing imagery of vegetation and rainfall to make short and medium term forecasting for the desert locust situation in the recession area (Cressman, 2008). The affected countries depend on the short term forecasts to plan the survey and the control operations; they also depend on the longer term forecasts for planning the campaigns of the desert locust control. On the other hand, the affected countries which use the forecasts should provide FAO with the feedback that improves the forecasting process (Cressman, 1997).

Two models are described by Cressman, (2008) and applied in DLIS by the SWARMS GIS software for analyzing data and forecasting the locust situation. The first model is the desert locust egg and hopper model which estimates the development of eggs and hoppers in days. This facilitates understand any given situation, estimating when undetected laying or hatching may have taken place, and predicting when hatching and fledgling may occur. The other model for the analysis and forecasting is the locust trajectory model, which estimates the displacement of adults forward or backward in time from any given point. This model uses 6 hours meteorological and forecast data for up to 10 days from the European Centre for Medium-range Weather Forecasts (ECMWF), consisting of temperature, pressure, wind direction and speed at several atmospheric levels between the surface and 500 hPa with a resolution of 0.25 to 1 degree square.

Another geographical information system also provided by FAO to the locust information departments in the countries of the recession area, called RAMSES (Reconnaissance and Management System of the Environment of *Shistocerca*). This software is used to analyze and display the survey data and the remote sensing images. In addition, the output data from RAMSES are used for monitoring daily the locust situation and the environmental conditions (Cressman, 2001; Ceccato, et al., 2007).

2.6. The Use of Remote Sensing and GIS for Investigating the Relationship between the Desert Locust and the Ecological Conditions

Few of studies have used the GIS analysis for the locust management research. Some researchers applied GIS on the locust monitoring by utilising the ground survey data only. While others linked the survey data with remote sensing images of the rainfall and the green vegetation cover to identify the likely breeding habitat for the desert locust.

Remote sensing images and GIS applications were used by Tappan, et al., (1991) in order to monitor the grasshoppers and the locust habitat in Sahelian Africa. They used the Normalised Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmosphere Administration (NOAA). Then, they integrated the data into a GIS with the digital cartographic data of the individual Sahelian countries producing image maps showing the vegetation green-up and dry-up patterns for monitoring the locust and grasshoppers activity. In addition, the effect of rainfall and vegetation on the desert locust breeding was studied by Voss and Dreiser (1994), who used the ground survey data of the desert locusts and the remote sensing imagery of rainfall and the NDVI, to produce a map showing the most likely breeding areas for the desert locust.

Furthermore, Anyamba, et al., (2005) used the locust survey data obtained from DLIS at FAO, and the NDVI of the SPOT-vegetation satellite and the rainfall data from NOAA, in order to analyze the ecological conditions associated with the recent locust precursor of late 2003 and the upsurge of 2004 in the northwest and Sahelian Africa. Moreover, the remote sensing imagery of Landsat Enhanced Thematic Mapper plus (ETM+) were used by Sivanpillai, et al. (2006), to map the likely breeding areas of the Asian Migratory Locust (*Locusta migratoria migratoria*) and to identify the reed areas within the river Lli delta of Kazakhstan. Then, they produced a land cover map by the digital processing of the satellite data in ERDAS GIS. On the other hand, the GIS techniques were applied for the desert locust management. For example, in a recent PhD thesis by Woldewahid (2003), the spatial autocorrelation between the solitary desert locust insects and the vegetation species of *Heliotrobium arbanese* and the millet plant was identified, in the range of 5 to 24 kilometres. A similar result for this relation was found in a study conducted by Werf, et al*.,* (2005) with the millet plant in the areas which do not have *Heliotorbium sp;* they concluded that the millet can be used as a guide plant for the solitary locust presence in specific areas.

Additionally, the geostatsitical procedure of kriging interpolation was used by Woldewahid, et al. (2004), for characterizing the spatial dependence of the desert locust density in order to evaluate the possibility of estimating the locust densities at the unvisited infested sites, based on the information obtained from the surveyed sites. Furthermore; Rong, et al*.,* (2006) studied the spatial distribution of *locusta migratoria manilenses* egg pods by integrating the geostatistical analysis and GIS; they used the block kriging and produced a risk assessment map showing the probabilities of the occurrences of locust egg pods at an area-wide scale. Morveoever, the kriging was used for mapping the precipitation in Switzerland by Atkinson and Lloyd, (1998).

2.7. Estimating the Green Vegetation Areas by Using the Vegetation Indices

The Enhanced Vegetation Index (EVI) is used in the current to study to identify and estimate the green vegetation areas prone to desert locust infestations. The vegetation indices of remote sensing data were not used previously to estimate the infested green vegetation area by the desert locusts. However, they were used in other field studies to estimate the green vegetation areas. For example, according to (Purevdorj, et al., 1998); the multispectral SPOT imagery was used by Dyamond et al., (1992) to estimate the percentage of vegetation cover in New Zealand. They related the percentage of the ground measurement of vegetation to the normalized vegetation index (NVI). While Fazakas and Nilsson (1996), determined the relation between the Thematic Mapper estimates, together with the information of the forest vegetation cover over southern Sweden on one hand, and the (NOAA / AVHRR) pixels which cover the same location on the other hand, using regression analysis to build the relation.

In addition; the percent vegetation cover area was estimated in the grassland in Mangolia and Japan by Purevdorj, et al. (1998), using simulated AVHRR vegetation indices data of NDVI, the soil-adjusted vegetation index (SAVI), the modified soil-adjusted vegetation index (MSAVI) and the transformed soil-adjusted vegetation index (TSAVI). Furthermore, Hereher (2009) used the NDVI to estimate the agriculture land area in Egypt in the year of 2005.

2.8. The Contribution Which the Study Can Make to the Body of Knowledge

The above mentioned studies investigated the effect of the ecological conditions on the desert locust and used the survey data for the desert locust forecasting by applying the GIS techniques. While the current study, investigates the effect of two important ecological conditions including the rainfall and the green vegetation on the desert locust breeding and infestations, by utilising the remotely sensed data and the GIS applications. In addition, the current study assesses the effect of elevation on the locust infestations using the Digital Elevation Modelling (DEM), as it can be noticed from the above mentioned works that no study has investigated the elevation effect using the remote sensing and GIS application.

Furthermore, the current study uses the remote sensing images of green vegetation and survey data to assess the likely infested and the likely breeding areas, by estimating the area of the green vegetation in which infestations or breeding occur. The size of the green vegetation cover is going to be estimated using the EVI.

As discussed earlier, FAO prepares a monthly bulletin based on the forecasting carried out at DLIS; this demonstrates where the infestations by the desert locust can occur in the next months of the forecasting. Based on the FAO forecasting, the study makes contribution by devising a means to identify and estimate the expected infested and breeding areas prior to the occurrence of an invasion by the desert locust swarms or individuals. The estimated areas are compared by the survey planners with the areas which are covered by the survey teams, and then surveyors can be asked to carry out surveys in the non-surveyed areas.

This can be performed by utilising the EVI to estimate the green areas which are prone to infestations or invasions by the desert locust (likely infested and breeding areas). The proposed means can target the survey teams to the most suitable survey targets. Moreover, the study defines a method that estimates the area infested after conducting an assessment survey and using the information provided by the survey teams about the infestation size in the surveyed areas, to predict the infestation areas in the unvisited sites. Then, these areas can be considered the next survey targets, which are likely to contain the most infestations.

Chapter Three: Methodology and Data Analysis

3.1. Work Design

The required data were collected from the primary and secondary sources and were integrated with the ArcGIS 9 software. A sequence of steps was applied in order to achieve the aim and objectives of the research as described below:

The first part of the thesis realizes the first objective and answers first research question, which are concerned with investigating the effect of the rainfall, the green vegetation and the elevation on the infestations and breeding of the desert locust. To realize that, the following steps were followed:

- Remotes sensing imagery of the monthly rainfall, the green vegetation (EVI), and the DEM for the area are processed by ArcGIS 9 software. The EVI layers were classified into various ranges of values to observe in which range the significant infestations by the desert locust occurred (See section 3.4.1).
- The survey data of the locust infestation types were refined and classified into monthly files, in order to be added as event layers over the vegetation and rainfall layers.
- Then, the monthly vegetation layers were added over the monthly rainfall layers, to produce maps displaying the effect of rainfall patterns on the growth of the green vegetation, and the event layers of locust infestations were added on them, to determine where infestations occur in relation to the EVI values. And;
- Finally, all the infestations were added as event layers over a background layer of elevation, to specify at which elevation levels the infestations occur.

The second part of the thesis is related to the second and the third objectives, and responds to the second and the third research questions, which are concerned with identifying and estimating the likely breeding areas and the likely infested areas by the desert locusts. This requires the application of two methods:

- The first method is to identify and estimate the size of the green vegetation in the EVI value ranges and the elevation levels, where infestations by the desert locusts mainly occur, and;
- The second method applies the kriging interpolation technique using the survey data. The values of the infested areas in the visited sites by the survey teams are interpolated to predict the sizes of infestation in the non-surveyed areas.

3.2. The Study Area

The study area is Abu Ramad, which is located to the south east of Egypt between latitudes 22 to 22.7 N, and longitudes 35.5 to 36.85 E (Figure 3). The area is a winter breeding area and is known to have repetitive desert locust infestations, especially after the rainfall occurs in winter and the green vegetation grows up. The habitat of the area includes seasonal riverbeds (wadies), and sandy soil plains intersected by hills and mountains (Cressman, 2000). Control operations in this area and the neighbouring areas against the desert locust were conducted recently in the 2004 / 2005 winter season.

The choice of this area depended on the availability of the survey data which are used in the study. In addition, the area is situated around the Red Sea coast where desert locusts are abundant during the recessions in the central region, where overlapping rainfall regimes and the breeding of the desert locusts begins in one season and extends to the next and sometimes into many months (Skaf, Popov and Roffey, 1990).

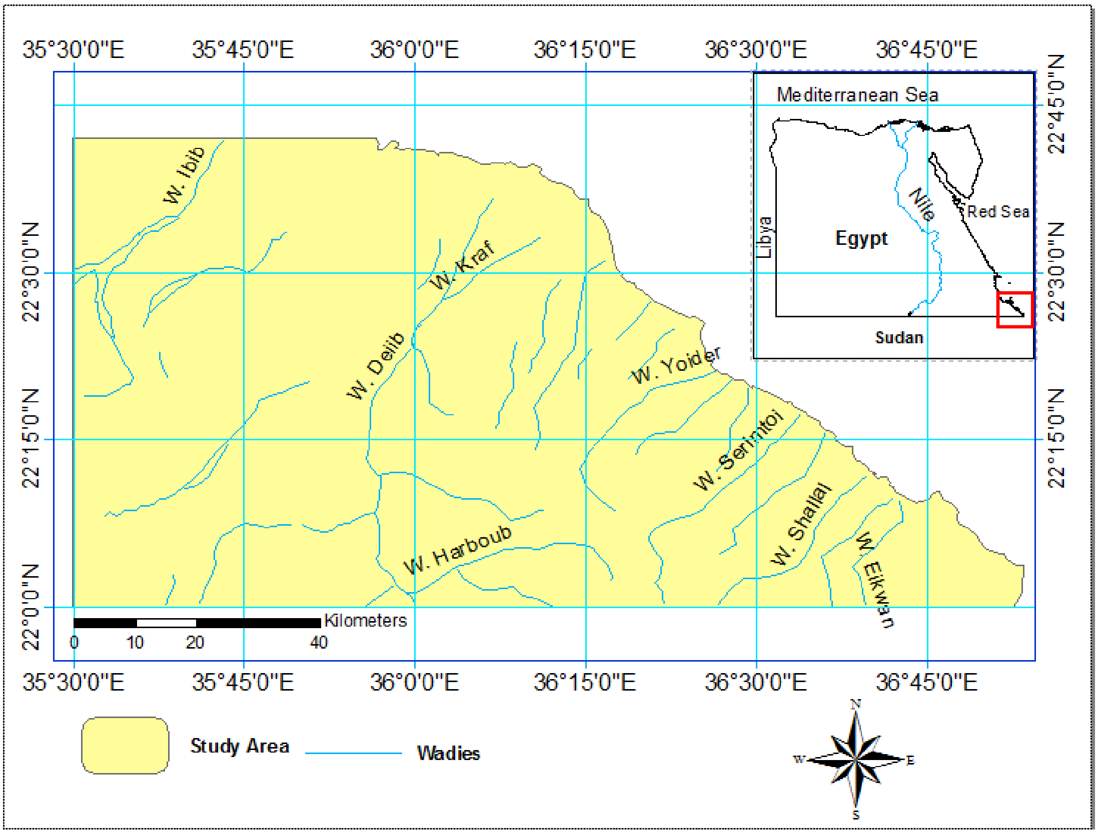


Figure 3: The study area

(Marked with the red square on the upper right frame box on the map)

3.3. Data Collection

The study utilises intensive qualitative and quantitative data, there are primary and secondary data: the primary data are collected by the survey team (including the author) in the study area in the winter seasons of 2004 to 2008. The secondary data are the remote sensing imagery.

3.3.1. The Primary Data

The survey methodology: the surveys are conducted in the green vegetation areas suitable for infestation or breeding by the desert locust, at each survey site, the surveyor either walks for a distance of 100 to 300 meters looking at both sides for a distance of 2 meters wide, and recording the observations about the desert locusts and the environment. Or, he gets into a vehicle which is driven for a distance of 1 kilometre against or cross wind direction, counting the insects which fly through the front glass window. The survey data are recorded in the FAO desert locust survey and the control form (Appendix 2) (Cressman, 2001); these data include the following:

1- The location: the name, the coordinates of the location and the date of survey.
2- The environment, such as the type of the habitat (wadies, plains, crops, wells or sand dunes), the rainfall amount and the date of last rain; the soil type and moisture, and the vegetation in the area (green or dry, light, medium or dense). In addition to the size of the surveyed area at the survey stop and the size of infestation (if found).
3- The desert locusts: (present or absent), the type of infestation if present; are they hoppers, adults or egg fields; the Locust phase (solitary, transient or gregarious) and the maturity of the adult insects, if found (mature, immature or maturing)
4- The control operations (were they performed or not), if performed, the information about the type of control (air or ground) should be recorded, together with the name and the application rate of the insecticide used (Quantity per hectare) and the total quantity used for the control.
5- Any other comments noticed by the surveyors in the survey location.

- **<u>The survey equipments</u>**

- Maps of the survey area, the desert locust survey and the control form for recording the data.
- Global positioning Systems (GPS) Garmin 12 XL, used to measure the geographic coordinates of the survey stops as latitudes and longitudes.
- The e-locust device used in recent years to record the data, measure the coordinates automatically, and send the data directly via satellites to the locust control headquarters.

The study utilised only the important data according to its requirement. The data utilized include the survey date, the coordinates of the survey stop, the infestation sizes to be used for interpolation, and the type of desert locust infestations.

- **<u>Refining the survey data</u>**

The survey data were sent from the locust headquarter of Egypt. They were extracted from the RAMSES software as .dbf database file format and were converted into. xls spreadsheet file format and sent by e-mail. These data represent the survey results all over the country covering the years 2004-2009. Therefore; the survey data which represent the study area were selected and extracted into a separate file, for the years 2004-2008. Then, they were divided into separate annual files which in turn were subdivided into sheets representing the months from October to March covering the winter season survey period in Egypt. The data representing the other months (April to September) were removed. In addition; some data were sent as reports or survey forms, they were used to increase the number of the survey data required for the study analysis.

It was found out that some of the data records have some errors; these data were removed in order to avoid their effect on the analysis. For example, in the field of one record, the data point to an infestation in a certain area, while another field in the same record informs that locust was absent; in such instance the record was removed from the data. Such discrepancies were unusual and their removal did not adversely affect the large body of data, as those records represent less than 1 % of the data.

3.3.2. The Secondary Data

The secondary data includes the remote sensing images of the vegetation and the rainfall in the study area for the period 2004-2008. The vegetation layers were downloaded from The Moderate Resolution Imaging Spectroradiometer (MODIS/ TERRA V005), and a DEM layer from ASTER. "These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (lpdaac.usgs.gov).".

The temporal resolution of MODIS vegetation data are 16 days, at 250-meter spatial resolution, as a gridded level-3 product in the Sinusoidal projection (SIN) (NASA / LP DAAC, no date). 48 layers were downloaded from MODIS of NASA (National Aeronautics and Space Administration). The EVI is chosen because: it enhances the vegetation signal, it is considered an improved NDVI with an improved sensitivity to high biomass regions and improved vegetation monitoring capability, by decoupling the canopy background signal and reducing the influences of the atmosphere (Didan and Yin, 2002; and Matsushita, et al., 2007). Therefore, it is not be easily saturated by the chlorophyll or the cloud cover. Moreover, it is less affected by the reflection of dust particles in the air. Additionally, the EVI uses the near-infrared (NIR) wavelengths, in which vegetation and water can always be separable (Lillesand, Kiefer & Chipman, 2008). The EVI is calculated by the following formulae:

$$EVI = G \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 \rho_{red} - C_2 \rho_{blue} + L}$$

Where, p is the atmospherically correct or partially correct (Rayleigh and ozone absorption) surface reflectance. L is the adjustment of canopy background which addresses the non-linear difference NIR and the red radiant transfer through a canopy. C1, C2 are the coefficients of aerosol resistance term, which uses the blue band to correct the aerosol influences in the red band. The EVI coefficients adopted in MODIS algorithm are; L= 1, C1 = 6, C2 = 7.5 and the gain factor (G) = 2.5 (Didan and Yin, 2002)

The rainfall layers were downloaded from Tropical Rainfall Measuring Mission (TRMM), which is an endeavour between NASA and Japan's National Space Development Agency, designed to monitor and study the tropical rainfall and the associated release of energy. This data was downloaded in a NetCDF format, produced by the global rainfall algorithm of 3B43, which combines the estimates generated by the combined instrument rain calibration (3B 42) and the global grid rain gauge data from CAMS produced by NOAA's climate prediction centre and the global rain gauge product produced by the Global Precipitation Climatology Centre (GPCC), together with the out put is monthly rainfall with 0.25 x 0.25 degree spatial resolution (NASA/GESDISC/MIRADOR, no date). The data value units are mm/hour. The rainfall data is global data covering the area within the longitude 180 W to 180 E, latitude 50 S and 50 N (NASA / GES DISC, no date).

The DEM layer is used to reveal the effect of elevation on the desert locust infestations and breeding. This layer was downloaded from ASTER satellite (from NASA) with the geographic coordinate projection system. The DEM is an ordered array of ground elevations relative to a datum. It is normally expressed as meters above the mean sea level, and is referenced to the geographic coordinate systems using latitude and longitude or to the plane coordinate system such as the Universal Transverse Mercator System using meters (DEM definition no, date).

3.4. Data Analysis

3.4.1. Analysing the Effects of the Ecological Conditions on the Desert Locust

The remote sensing layers of the rainfall, vegetation and DEM were processed by ArcGIS 9.2 and ArcGIS 9.3, which were also used for analyzing the survey data.

- **Processing the rainfall layers**

The TRMM rainfall layers were added to the ArcGIS 9.2 software as NetCDF files and were converted to raster, and then they were clipped to cover all parts of the study area. The hourly rainfall were converted into monthly rainfall amounts (millimeters), by multiplying them by the number of hours per month, in order to get the monthly rainfall amounts in millimeters (NASA / GES DISC, no date).

- **Processing the vegetation layers**

The EVI layers (with the .hdf extension) were classified into various ranges, and to symbolize these various ranges to show their extent and sizes in the study area across the four winter seasons. The following steps demonstrate the processing procedures of the raster EVI layers:

1) The images were added into ArcGIS 9.3, re-projected from the SIN to the geographic coordinate system of ITRF 2000 which is the projection system of the study area boundary map, so that the boundaries of both layers can be plotted in the same location (Heywood, Cornelius and Carver, 2002 & 2006). Then; they were clipped according to the boundary of the study area, by using the clipping function of the raster layers in the ArcGIS 9.3.

2) The EVI layers represent 16 days temporal resolution, so that the clipped images were combined into monthly composite images, by using the raster calculator function of the ArcGIS 9.3. Every compound image represents one month; it consists of two layers of the same month, so that the monthly infestations data could be added to the compound images of the same month when the surveys were undertaken.

3) The EVI values of the composite images were multiplied by 0.0001 using the raster calculator, in order to get the real EVI value in the different parts of the study area (NASA / LP DAAC, no date).

4) Then, every compound EVI layer was classified into ranges of values (< 0.05, > 0.05 to 0.1, > 0.1 to 0.2, > 0.2 to 0.3 and >0.3 to 0.5). This was carried out by using the reclassify function, and the raster layers were converted into vector ones, forming a vector layer for every EVI value range. Each vector layer represents a specific range was given a specific symbol to differentiate it from the other ranges, and to show which EVI value will contain the significant infestations. The EVI range values were symbolized as follows:

- Vineyard for the range of < 0.05
- 10 % simple hatch for the range of > 0.05 to 0.1

- 10 % crosshatch for the range of > 0.1 to 0.2
- Mangrove for the range of > 0.2

5) To estimate the vegetation areas, the number of pixels represents every EVI range was divided by the total pixels count of the compound raster layer. The resulted fraction was multiplied by the boundary size of the study area, which equals the same size of the composite raster image. The result of this calculation is the size of the green vegetation cover for this range in the entire study area.
6) The data resulted from the last step were extracted as .dpf files and opened with the excel software, in order to calculate the sizes of vegetation in the various ranges of EVI values.

- **Processing the DEM layer**

Two DEM sheets cover the study area (with .hdf extension). The layer sheets were added to the ArcGIS 9.3 software, and were clipped according the study area boundary. After that, they were symbolized by classifying the elevation value into six classes in meters (<100, 101:200, 201:300, 301:400, 401:500 and 501:1800 meters) in order to differentiate the diverse altitude values of the study area, and to find out at what elevation range the desert locust infestations and breeding occur.

- **Symbology of the survey data**

After classifying the survey data into monthly files (according to the dates of surveys), the survey data were given individual numbers and symbols according to the type of infestation, in order to plot them on the vegetation layer as follows:

- The non-infested survey locations were given a blue circle symbol.
- The solitary hoppers infestation spot took a dark blue circle symbol

- The gregarious hopper was given a yellow circle symbol.
- The solitary adult infestations were given a grey circle symbol.
- The gregarious adult infestations were given a red circle symbol.

- **Overlaying layers**

The EVI layers were added over the monthly rainfall layers, in order to compare the rainfall amounts and the vegetation condition of the same month, by employing the visual comparison. The monthly infestation data were also added as event layers on the EVI layers, and were symbolized as stated earlier according to the type of infestations, in order to reveal the effect of green vegetation condition on the desert locust visually. Furthermore, all infestations were added to the DEM layer, to display the elevation level effect on the locust infestations by visualizing the elevation level at which infestations occur. The spatial join was used to confirm at which ranges the infestations occur within the elevation levels and the EVI value ranges, in order to specify the likely breeding and likely infested areas.

- **The relationship between the rainfall and the green vegetation**

In order to reveal the relationship between the rainfall and the vegetation growth, a rectangular area was chosen inside the study area (Figure 4), as the study area has a curved boundary neighboring the Red Sea and the rainfall grids in this boundary are covering other parts in the sea out of the study area, so the estimation of the rainfall in these parts cannot be made accurately. Then, the monthly rainfall were estimated inside the selected area across the four winter seasons, and also the vegetation areas were estimated inside the same area by the analysis of the rainfall and EVI layers in ArcGIS 9.2. A simple regression analysis was run, to determine the effect of rainfall as a predictor variable on the vegetation growth as a predicted variable (Chatterjee and Hadi, 2006).

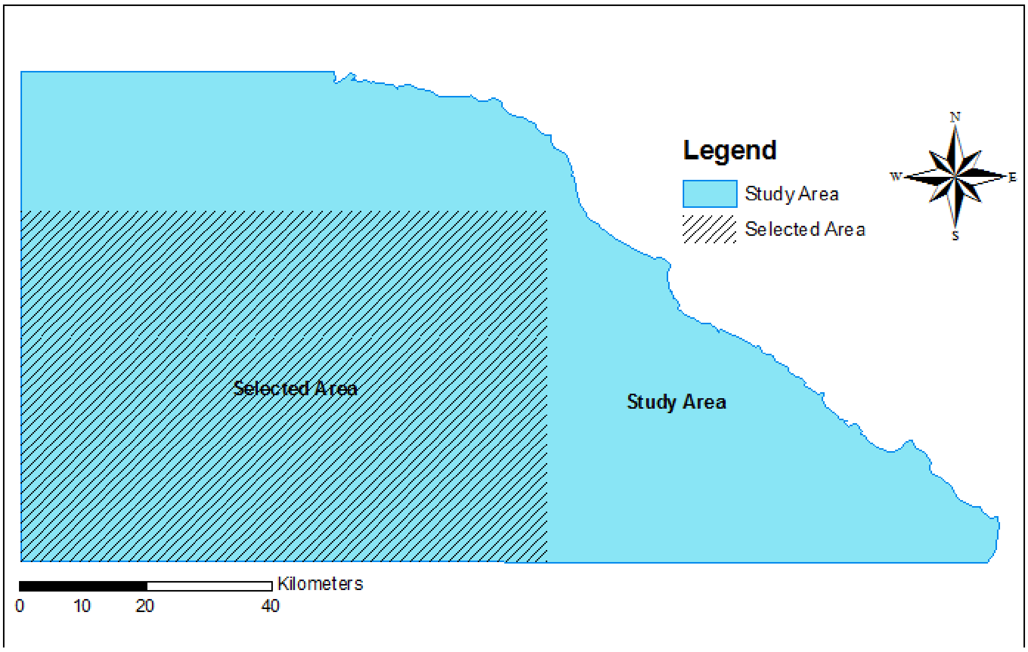


Figure 4: The selected area for estimating the rainfall amounts and vegetation area

The selected area was chosen as a rectangular area covered by six rainfall grids with 0.25 decimal degrees spatial resolution.

3.4.2. Estimating the likely Breeding and likely Infested Areas by the Desert Locust using the EVI and DEM

It should be noted that both the likely infested and the likely breeding areas are dynamic, as they depend on the extent of the green vegetation area in which infestations mainly occur. (Vegetation extent can be changed from one month or season to the next)

The likely breeding areas are the similar to the likely infested areas, but the likely breeding areas are found in the sandy places with recent rainfall, as breeding requires sandy soils for egg laying by the females of the desert locust. Therefore; the likely breeding area equals the green vegetation areas, which are found in the sandy soil places. This requires delimiting the sandy soil areas and subtracting the areas covered by mountains, hills and rocks (using scanned copy of the paper map of the area, or a digital map) from the size of the total green vegetation which are predicted to be infested, whenever infestation is expected to occur.

The estimation depended on plotting the survey data over the symbolised DEM and EVI layers which is classified into range of values as was mentioned earlier, and checked to specify the occurrence of the infestations. The likely infested and likely breeding areas are represented by the vegetation area within the EVI range where the most infestations occur, and at the elevation levels where the infestations mainly occur.

3.4.3. Using Kriging for the Prediction of the Infested Areas

The geostatistical analysis of the kriging interpolation technique was used to analyse the data obtained from the survey operations. This is to predict the size of the area infested by the desert locust in places not visited by the survey teams; (such places lack the sampled points) based on measuring the distance and the direction between these sampled points. The technique is based on the principle of spatial dependency which measures the relationship between near and distant objects. Interpolation is used to convert the data from point observations to continuous surfaces, so that the spatial pattern sampled by these measurements can be compared with the spatial pattern of other spatial entities. The interpolation is important here as the data available form the survey do not cover the area of interest completely (Burroughand and McDonnell, 1998; Childs, 2004) and the interpolation fills in the gaps between these measured values (Heywood, Cornelius and Sarah, 2000 & 2002). Kriging as described by Burroughand and McDonnell, (1998) is a multi-stage process of interpolation which builds upon the calculation and modeling of the experimental variogram. It forms weights from the surrounding measured values for predicting values at unmeasured locations; the weights come from semivariogram which is developed by viewing the data spatial structure (ESRI, no date).

The same kriging type was used for predicting infestation sizes, in order to get the same result of analysis, as the use of different methods of interpolation results in getting different results (Childs, 2004). The universal kriging was used to estimate the size of the areas infested by the desert locust using the data of the infestation sizes occurred in the years 2004-2008. The universal Kriging uses the regression model as a part of the kriging process, typically modeling the unknown local mean values as having a local linear or a quadratic trend. It is used because the mean infestation areas change substantially over very short distances, so it is described as non-stationary (Smith, De, Goodchild and Longley, 2006-2009*).*

The prediction of the infested areas in the current study is similar to that made by Woldewahid (2003), to measure the solitary desert locust densities in the non-surveyed sites by using the point measurements of locust densities at the surveyed sites located in the coastal area of the Red Sea in Port Sudan. Rong, et al., (2006) also used kriging for deriving risk map showing the egg pod distribution of *locusta migratoria manilensis* at an area-wide scale.

One can surmise that, kriging does not take the topography of the area into account; it considers the area as a plain surface and this can give values for infested areas over a mountain or a hill, although locusts do not breed over mountains, rather they stay sometimes over high altitude areas. However; this problem could be avoided by adding some points to the survey the data of zero values for the infested areas in the mountains and hills.

- **<u>Testing the accuracy of kriging as a method to estimate the infested areas</u>**

Cross validation is used to determine the suitability and performance of the model. Cross validation uses all the data for estimating the trend and autocorrelation models. It removes each data location at a time, and predicts the associated data value. So, it omits a point and calculates its location value using the remaining points, and then the predicted and actual values of the omitted points are compared. The same procedure is applied on the following points until the last point. Cross validation compares the measured and predicted data for all points (*ESRI, 2001 & 2003-2006; ESRI, no date*).

A scatter plot is produced for the predicted values versus the measured values. It is expected that these values should scatter around the 1:1 line (the black dashed line in the plot given below in Figure 5). However, the slope is usually less than 1, as it is a property of kriging which tends to under-predict large values and over-predict low values (*ESRI, no date*).

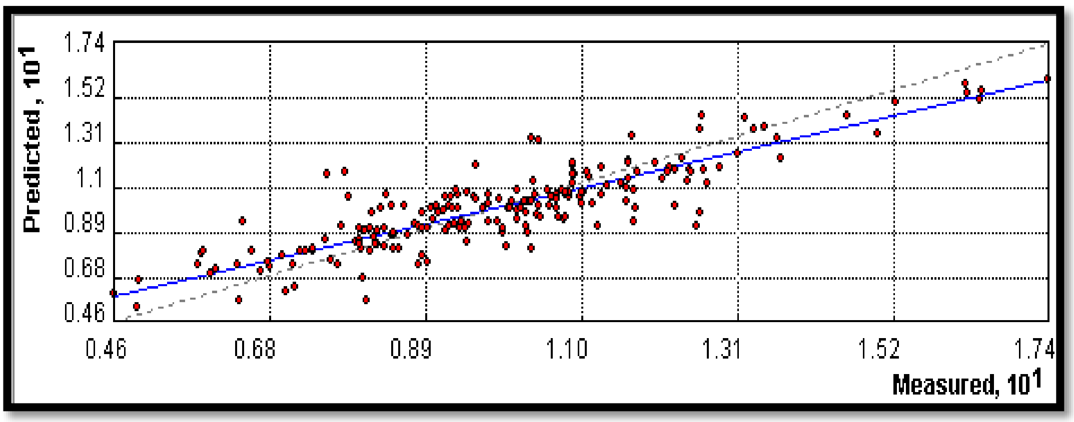


Figure 5: An illustration of the scatter plot

(*ESRI, no date*)

Chapter Four: Results and Discussions

4.1. The Effect of Rainfall, Vegetation and Elevation on the Desert Locust (Results of section 3.4.1)

4.1.1. The Effect of Rainfall and the Green Vegetation on the Desert Locust

Each of the produced maps displays the monthly layer of the classified EVI values over a layer of monthly rainfall, and an event layer of desert locust infestations that is added over them (the infestations events the survey stops). This demonstrates the relationship between the desert locust infestations on the one hand, and the vegetation condition and the rainfall on the other hand. The results are provided for the four seasons separately.

It can be noticed in the following Figures that the monthly survey data did not cover the study area regularly, as some of them are clustered in specific areas more than in other areas. The surveys were conducted in the preferred habitat for the desert locust, but some people conducted many surveys in the same locations throughout the same month. Besides, large parts of the area are covered by mountains and rocks where no surveys could be conducted; thus, the data could not cover the area completely. However, they still provide information about the desert locust and the habitat conditions in the most likely infested areas.

- **Assumptions**

- Null: means no infestations are found
- mm: means millimeters
- Infestations mean any type of infestation by the desert locust.
- Improvement or increase, and shrinkage or decrease in the EVI value means increase or decrease the size of the green vegetation found within this EVI value.

- **The winter season months of 2004-2005**

In general, that season had a good rainfall which led to the growth of green vegetation and provided suitable soil moisture content for breeding. The rainfall varied greatly in the study area through the winter months; it started with low amounts in October 2004, and increased during the next months. The green vegetation condition improved gradually to reach its top in the mid season, and then the dry conditions prevailed by the end of the season. The infestations appeared from the mid season to the end of the season. The following Figures show the condition for every month (Figures 6-11).

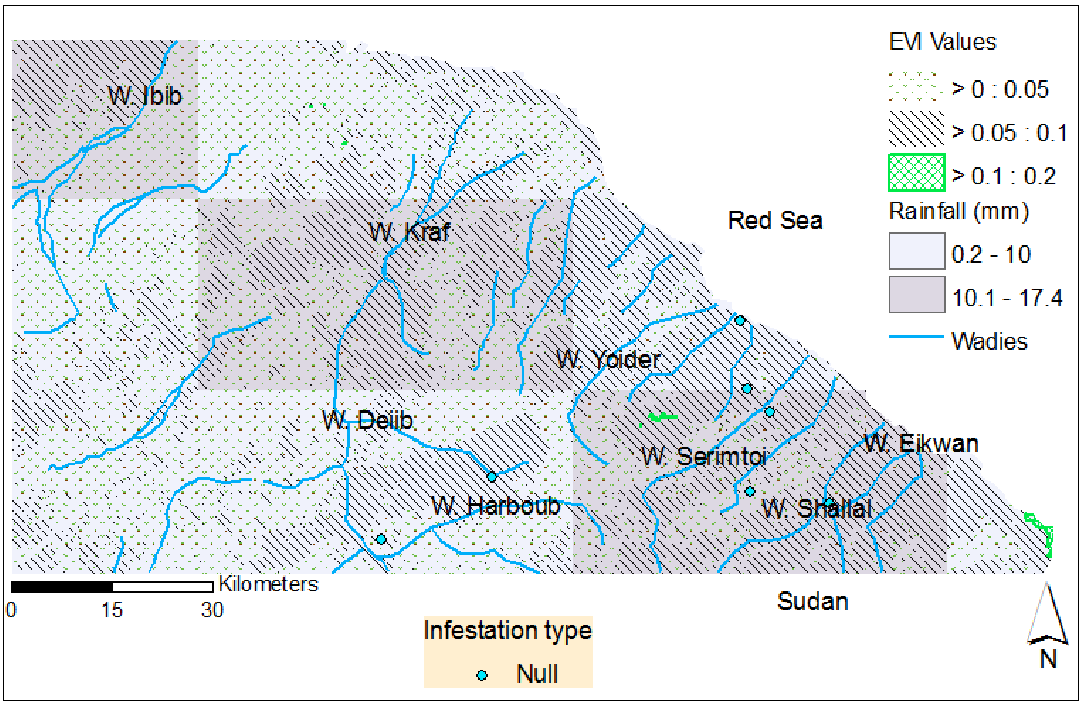


Figure 6: Rainfall, vegetation and locust infestations in October 2004

In Figure 6 above, the rainfall amounts in October 2004 varied across the area from less than 10 millimeter in the south west and some coastal parts, and > 10 to17 millimeters in the other parts. The EVI values varied across the area from < 0.05, > 0.05 to 0.1 which covered the largest vegetation area, and the small patches of vegetation in the range of > 0.1 to 0.2. There were no infestations in the study area, and the survey data were not enough.

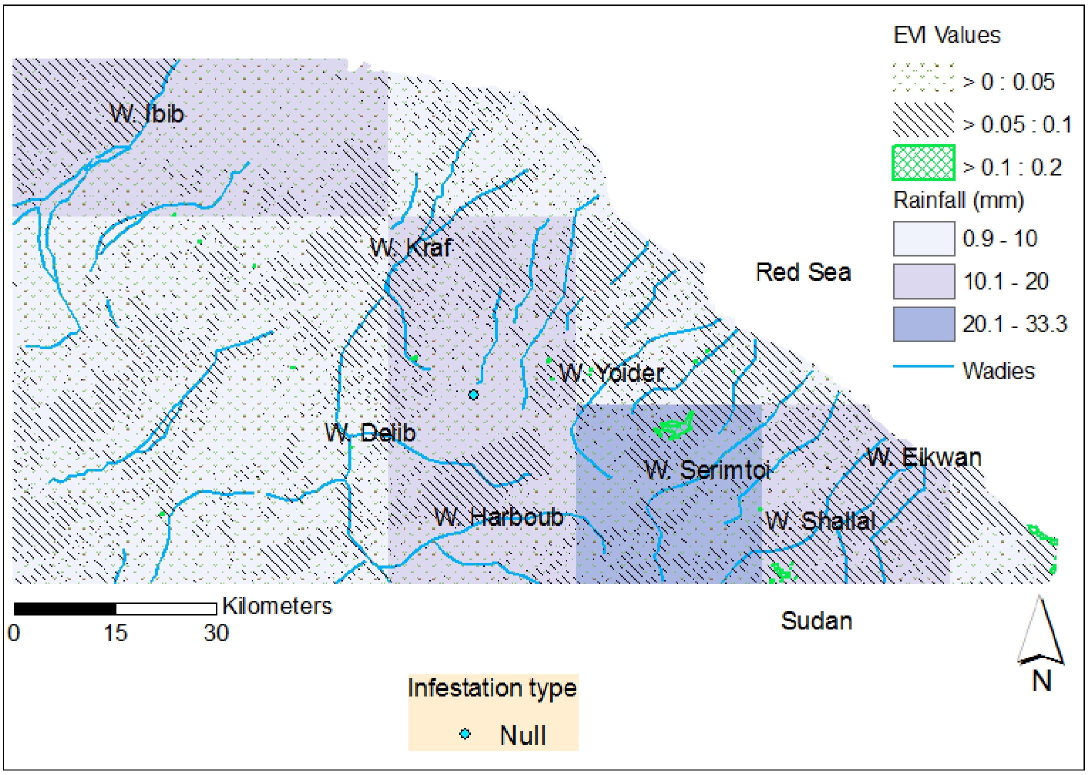


Figure 7: Rainfall, vegetation and locust infestations in November 2004

In November 2004, the rainfall amounts reached 20 to 33 millimeters in the south eastern part of the area, but the other parts were covered with amounts fewer than 20 millimeters. The EVI improved slightly in the range of > 0.1 to 0.2. The infestations were not found in this month, where only 1 survey stop was undertaken (Figure 7).

In December 2004, the rainfall amounts reached 20 to 28 millimeters. However, they were lower in the western and coastal parts of the area. EVI improved in the range of > 0.1 to 0.2, since numerous patches appeared in various parts of the study area. Solitary adult insects were found beside the coastal area, within the monthly EVI of > 0.05 to 0.1 (Figure 8).

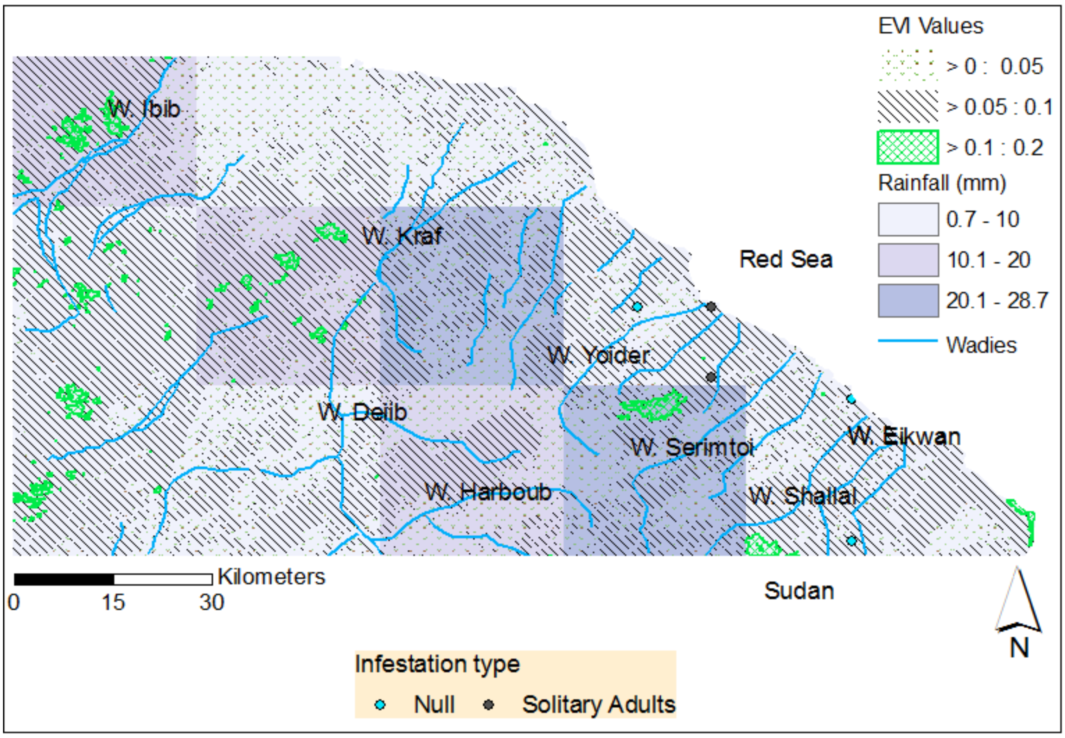


Figure 8: Rainfall, vegetation and infestations in December 2004

The infestations in December followed other infestations in the coastal area of the Red Sea to the north of the study area, after the invasion of the desert locust swarms to Egypt at the end of October 2004; some of them migrated to the east of the country, then to the winter breeding areas to the north of the study area (FA0, 2004a, c). Then, they might have migrated to the study area after the occurrence of rainfall in November and December 2004.

In January 2005, the rainfall increased to 45 millimeters in the eastern parts, but there was no radical change in the EVI. There were infestations including gregarious hoppers and gregarious adults concentrated in the inner area, in Deiib wadi within EVI range of > 0.05 to 0.2 (Figure 9). These infestations were predicted by FAO, being hopper groups and bands from mid January on forth in the area (FAO, 2005a, b).

The gregarious hoppers and adults occurred after the migration of the desert locust adult populations from the north of Egypt to the Red Sea east coastal plains in the south of the country. Some of them matured sexually and laid eggs, which hatched into hoppers after the rainfall occurrence in the area (FAO, 2005a).

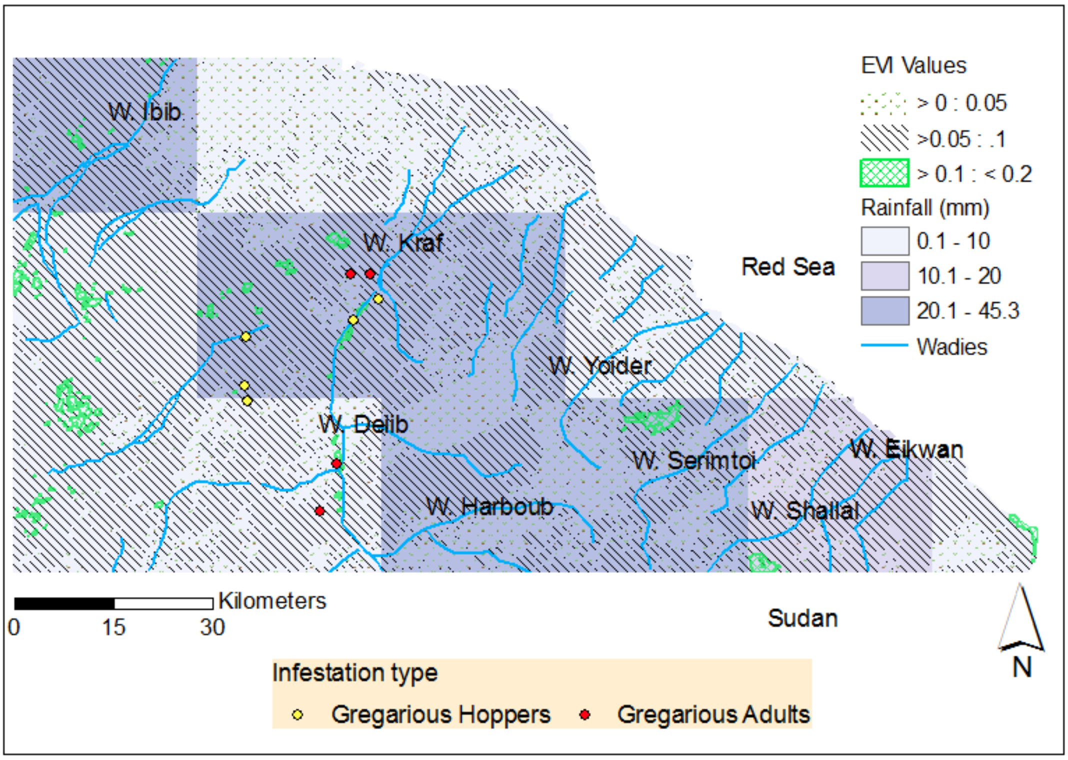


Figure 9: Rainfall, vegetation and infestations in January 2005

In February 2005, light rainfall occurred and the green vegetation size and extent shrank in the EVI value range of > 0.1 to 0.2. Infestations of hoppers increased; they were found within the EVI range of > 0.05 to 0.2 in Deiib wadi, and in the western parts of the area. Additionally, there were gregarious adults in Deiib wadi, and solitary hoppers to the east of the area (Figure 10). Those infestations were reported in the FAO forecast (FAO, 2005c). The increase in locust infestations might have occurred by the support of many swarms, which reached the winter breeding coastal areas of the Red Sea in the south of Egypt and north of Sudan. The adult insects might have resulted from the development of the previous month's hoppers, and /or from the migrated adults from the north of Egypt as believed by FAO forecast (FAO, 2005b).

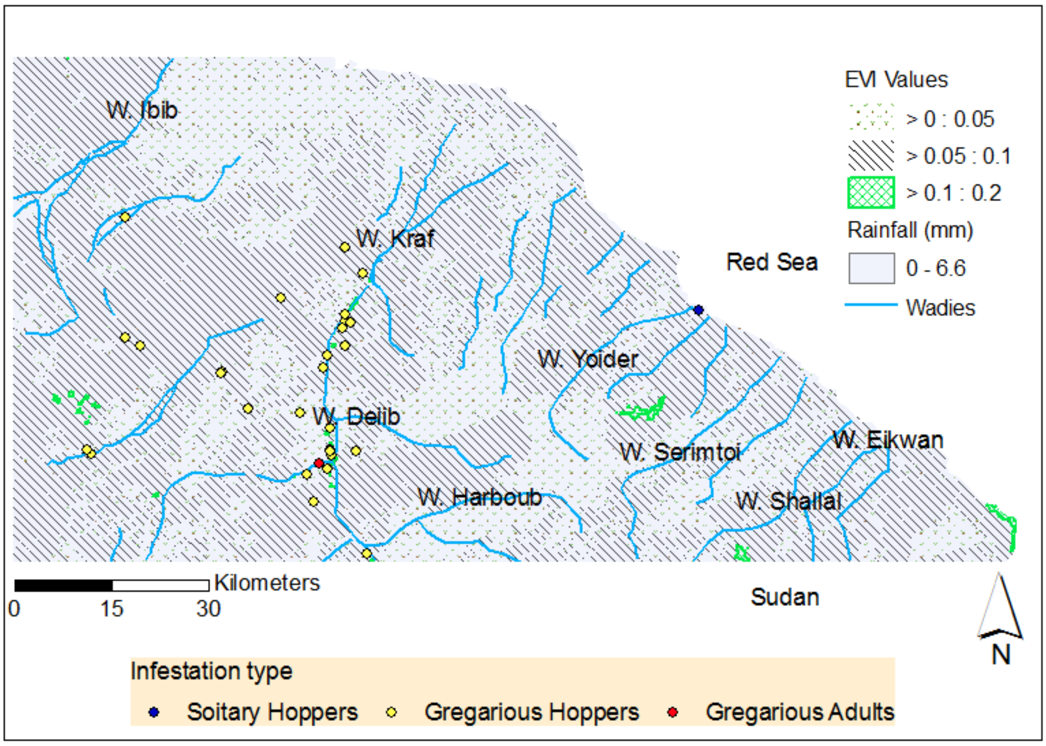


Figure 10: Rainfall, vegetation and infestations in February 2005

Good rainfall occurred in March, in the eastern half of the area with a maximum of 200 mm. The EVI range of > 0.05 to 0.1 increased; however, it shrank in the range of > 0.1 to 0.2 .The infestations were characterized by the gregarious hoppers and the solitary adults in Deiib, wadi; there were gregarious hoppers in the coastal areas too (Figure 11). These infestations were forecasted by FAO, as hopper bands were present in many parts including Deiib wadi, and as the infestations developed; some hoppers could develop to fledglings and adults (FAO, 2005d). It can be noticed from Figure 11, that the infestations and breeding declined in March, due to the control operations against the desert locust in the study area and the surrounding areas. However, small scale breeding continued in April 2005 (FAO, 2005e).

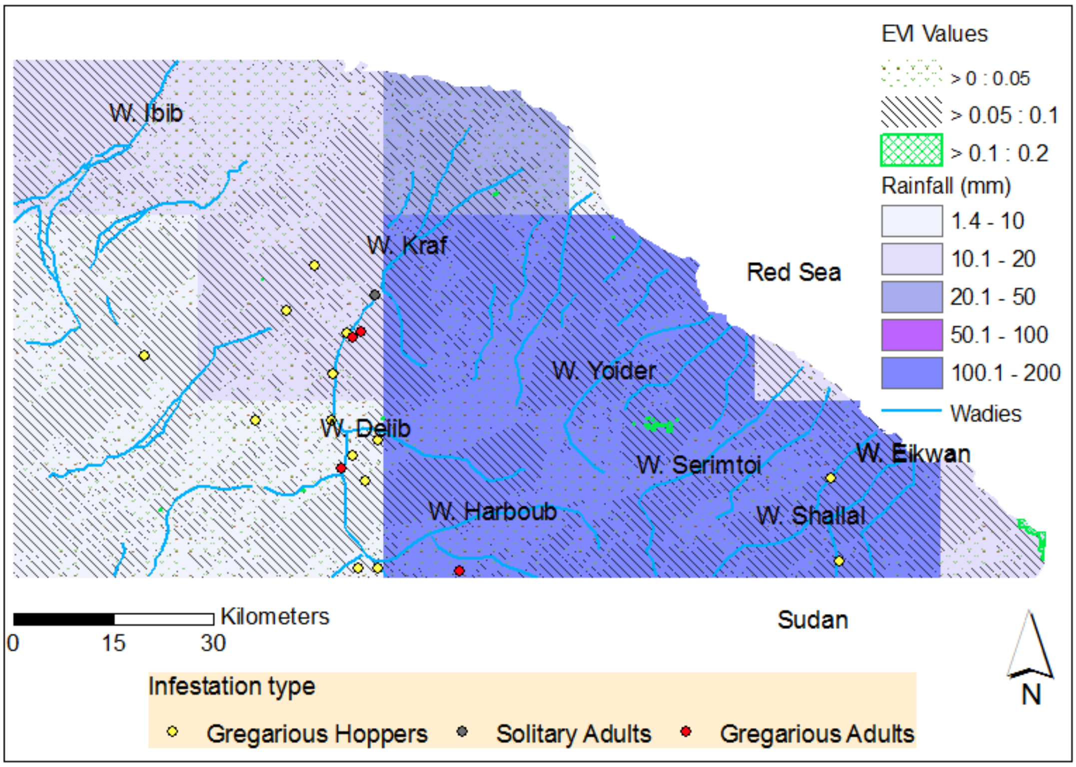


Figure 11: Rainfall, vegetation and infestations in March 2005

- **The winter season of 2005/2006**

In general, the winter season was a dry season characterized by the non occurrence of rainfall at the beginning, and very low precipitation in the mid and late season. The EVI values were very low and they varied slightly throughout the season months. Due to these non- suitable environmental conditions, there were recession and complete absences of the infestations during the season (Figures12 to 17). These dry conditions prevailed throughout the entire region including the study area in October 2005 (FAO, 2005f), and continued in November 2005 in the south east of Egypt and the northern coast of Sudan (FAO, 2005g).

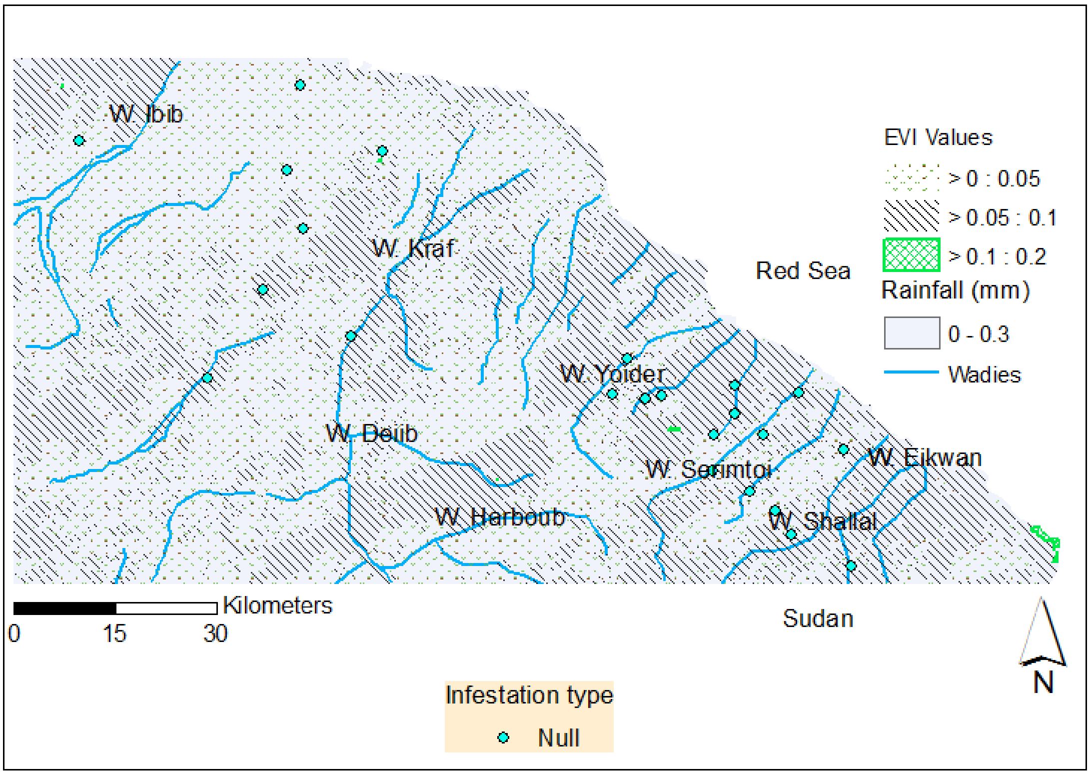


Figure 12: Rainfall, vegetation and infestations in October 2005

The above figure shows that only rainfall traces of less than 1 millimeter that occurred in October 2005 in all parts; there were no infestations in the area. Also, no infestations were mentioned in the FAO forecasts, in the study area during the period from December 2005 to March 2006 (FAO, 2005h; FAO, 2006a). However, the isolated adults were expected in the area after the improvement of the ecological conditions in north east of Sudan, which had infestations in Deiib wadi, 75 kilometers meters south of the study area (Deiib wadi extends from north Sudan to south Egypt).

In November 2005, only traces of rainfall occurred, but the EVI improved in the range of > 0.1 to 0.2, as there might be the effect of ground water. While in December 2005, light rainfall occurred with a maximum of 12 millimeters in the south of the area, and the EVI value decreased in the range of > 0.1 to 0.2 forming very small scattered patches. There were no infestations in both months (Figures 13 and 14).

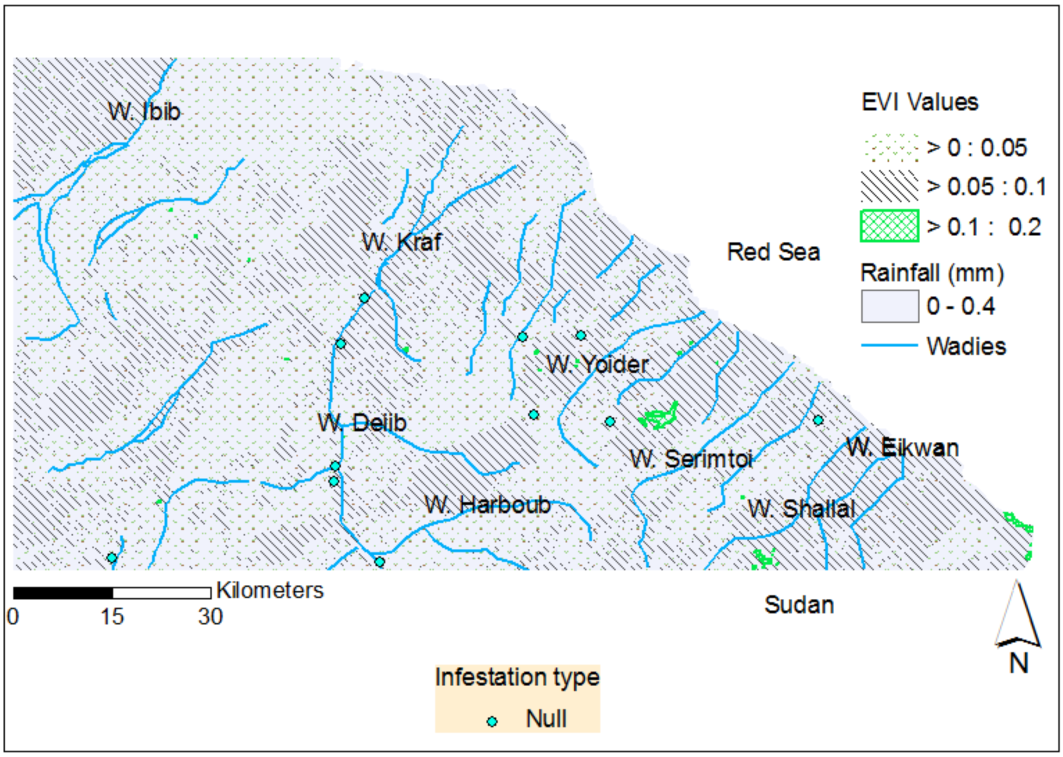


Figure 13: Rainfall, vegetation and infestations in November 2005

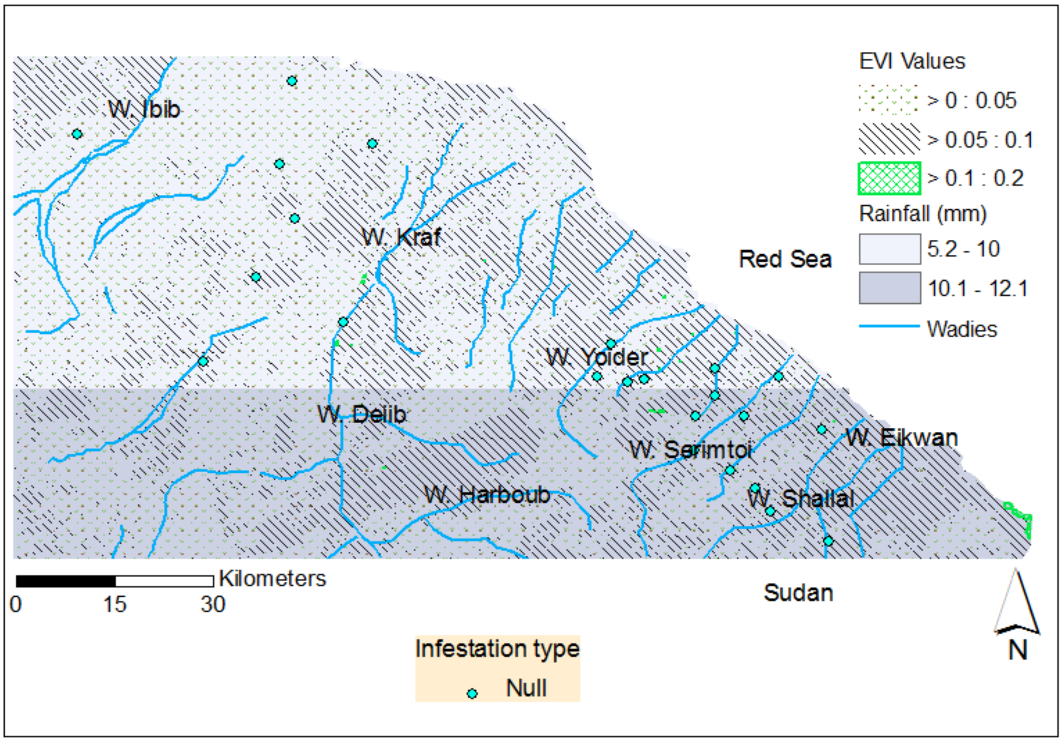


Figure 14: Rainfall, vegetation and infestations in December 2005

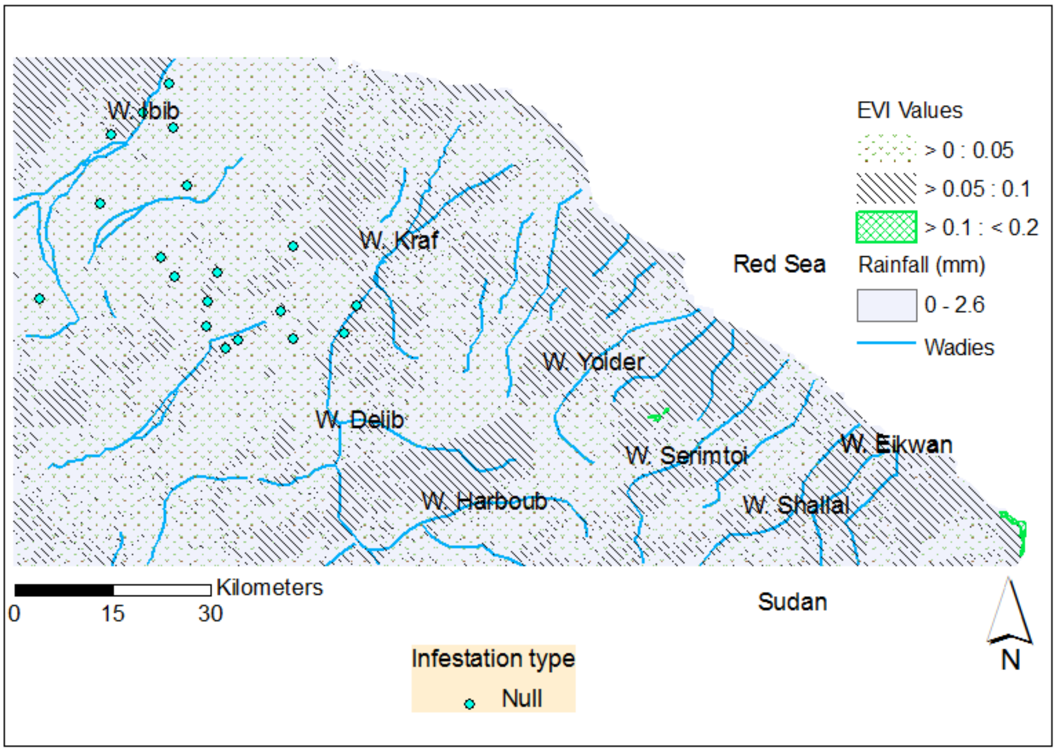


Figure 15: Rainfall, vegetation and infestations in January 2006

Figure 15 above shows a very light rainfall that occurred in January 2006 with less than 3 millimeters in all parts of the area. The EVI decreased in the range of > 0.05 to 0.2, and there were no infestations.

In February 2006, traces of rainfall occurred with no infestations although the vegetation conditions improved slightly in the EVI range of > 0.05 to 0.2 (Figure 16). Moreover, dry conditions prevailed across the entire coastal areas of the Red Sea; the infestations were unavailable, either (FAO, 2006b)

Light rainfall occurred in March 2006, but no infestations were found (Figure 17); also no infestations were found in March across the study area and the neighboring area of Sudan during the annual joint border locust survey in the Egyptian/Sudanese border area (FAO, 2006c).

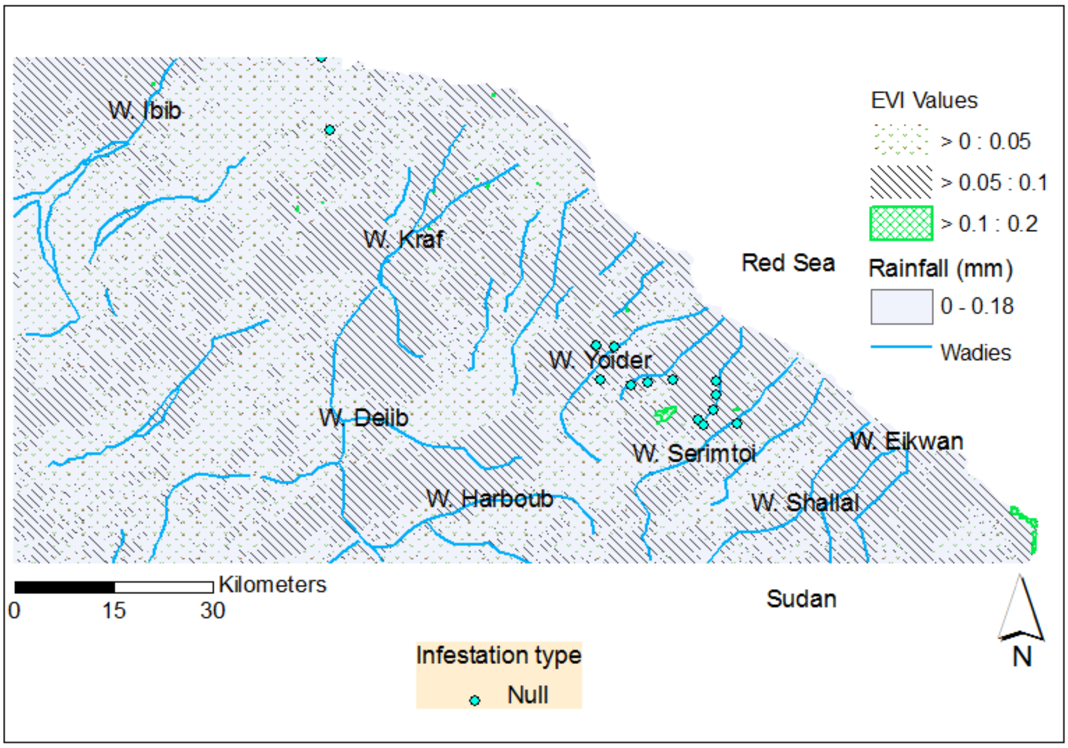


Figure 16: Rainfall, vegetation and infestations in February 2006

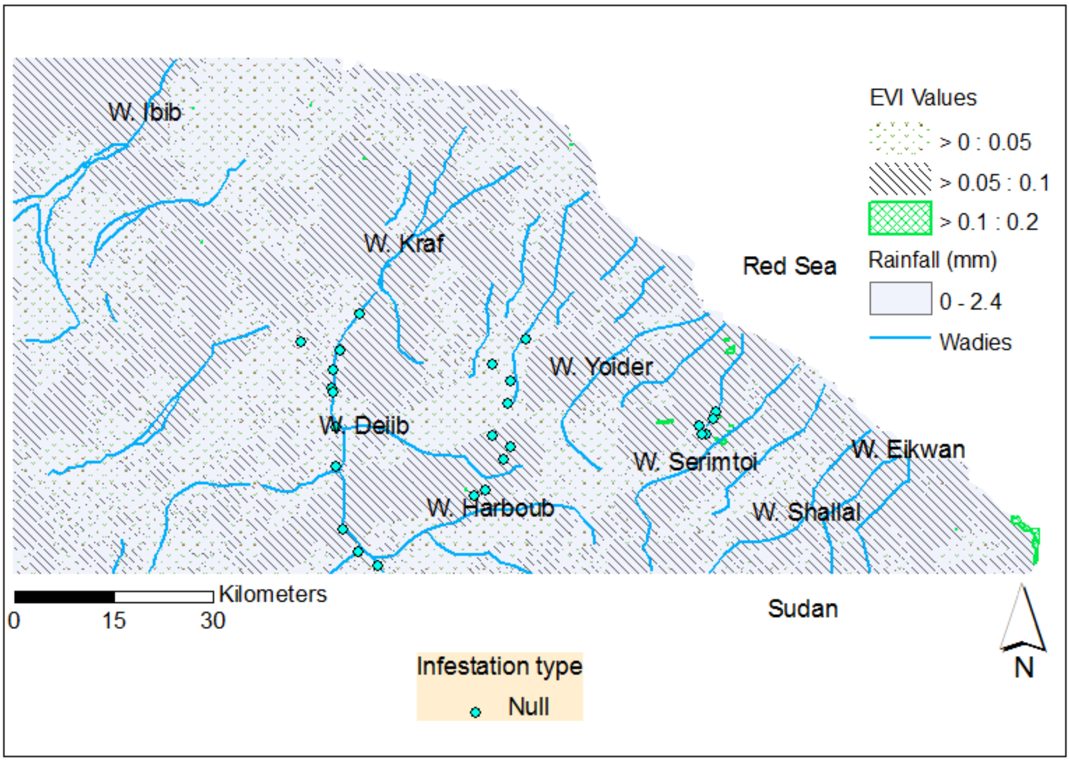


Figure 17: Rainfall, vegetation and infestations in March 2006

- **The winter season of 2006/2007**

The rainfall was low in the study area in the early season, very low in the mid season, and light rainfall occurred at the end of the season. The EVI values started with low values at the early season, increased slightly in the mid season, and improved by the end of the season. The solitary adult insects appeared at the middle and end of the season (Figures 18 to 23).

In October 2006, no infestations were observed. Light rainfall covered most of the area, but it was moderate in the south eastern and south western parts. The EVI values were low in the range of > 0.1 to 0.2, within which the vegetation was found as a scattered patch in the south eastern corner of the study area (Figure 18).

No rainfall or infestations were found in November 2006 also, although the EVI improved in the range of > 0.1 to 0.5, but the vegetation appeared generally as small patches (Figure 19); this might be due to the light rainfall in the previous month (Figure 18).

In December, solitary adult insects appeared in the south east of the study area in Eikwan wadi (Figure 20). This infestation was forecasted by FAO, as many isolated adults were found in the north east of Sudan (FAO, 2006d).

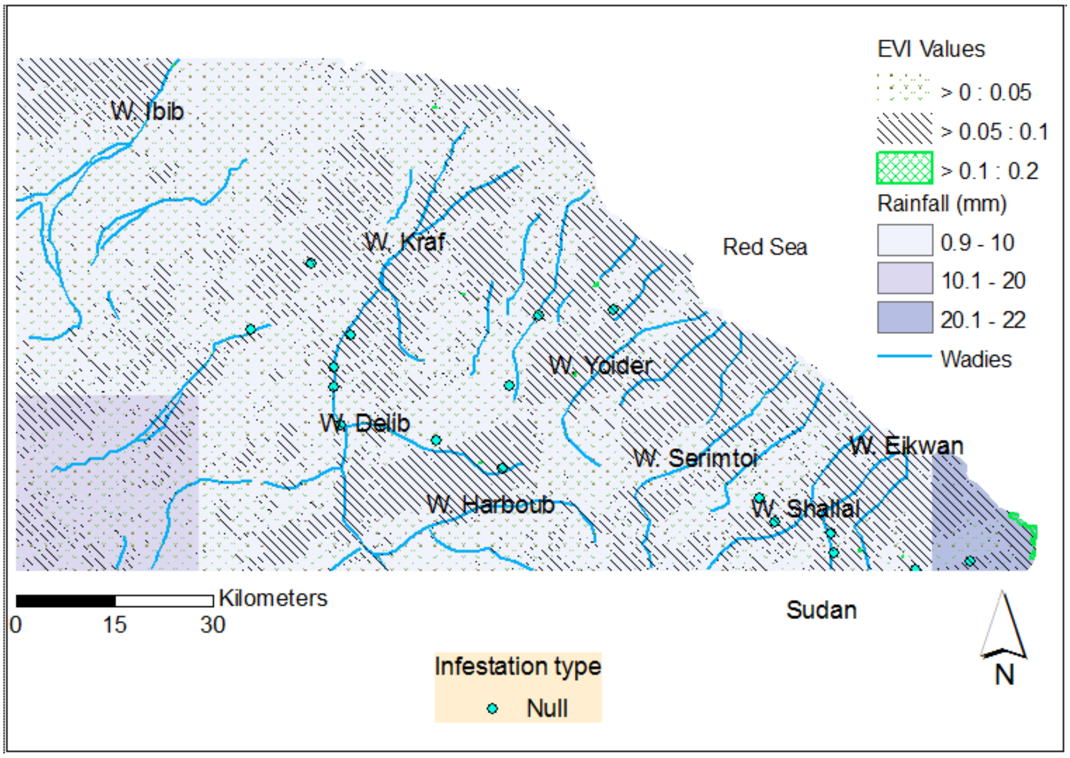


Figure 18: Rainfall, vegetation and infestations in October 2006

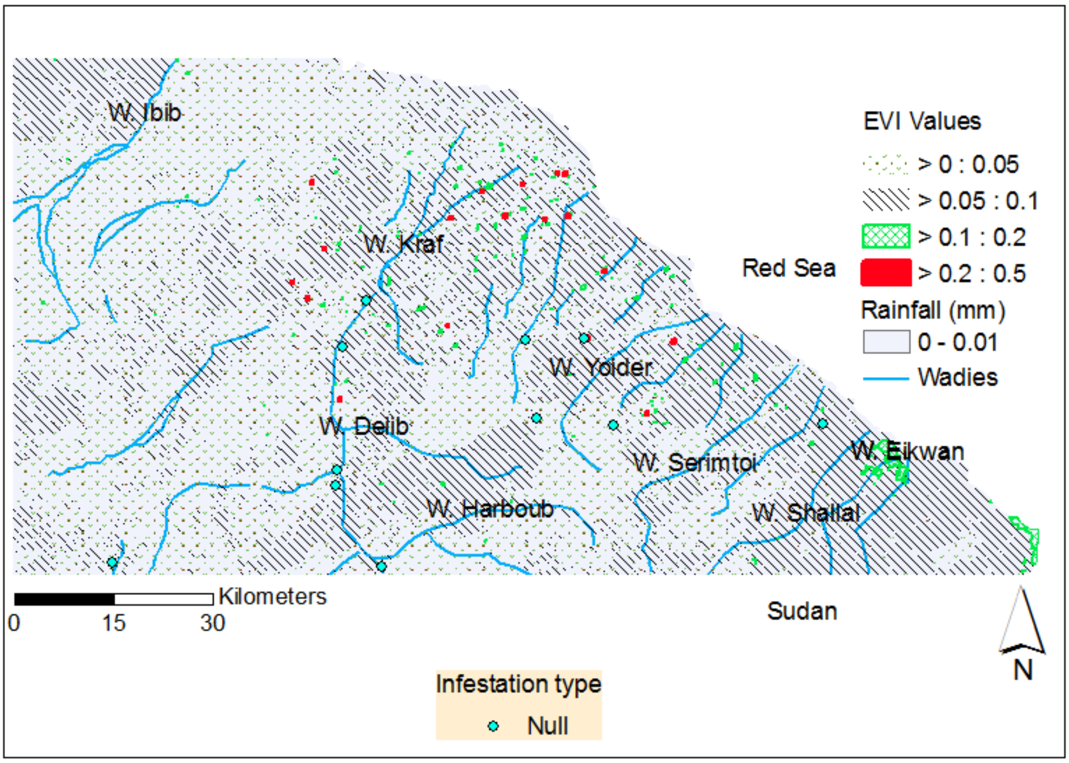


Figure 19: Rainfall, vegetation and infestations in November 2006

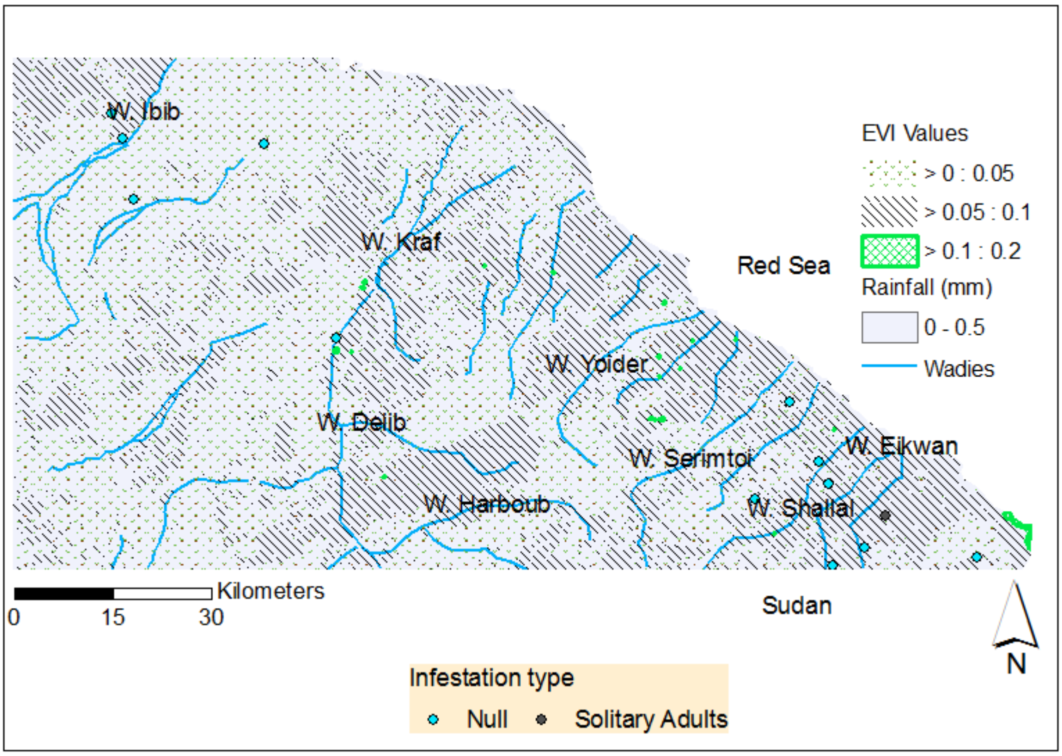


Figure 20: Rainfall, vegetation and infestations in December 2006

No rainfall occurred almost as it appeared in the above map, and the EVI values decreased in all the ranges, as a result of the shortage in the rainfall in the previous month and current month one too. Solitary adults were found in the south eastern coastal area, within the EVI range of > 0.05 to 0.1 (Figure 20).

There were no infestation during January 2007, when the rainfall occurred as the traces indicted, but the EVI improved in the range of > 0.1 to 0.2 in the south east of the study area (Figure 21). However, the vegetation was dry in the area and in the neighboring coastal areas, except in parts of Deiib wadi and in the south coastal area (FAO, 2007a).

Light rainfall occurred in February 2007 with a maximum of 5 millimeters, and the EVI increased slightly in the range of > 0.05 to 0.1, but it shrank in the range of > 0.1 to 0.2. Additionally, no infestations were found (Figure 22).

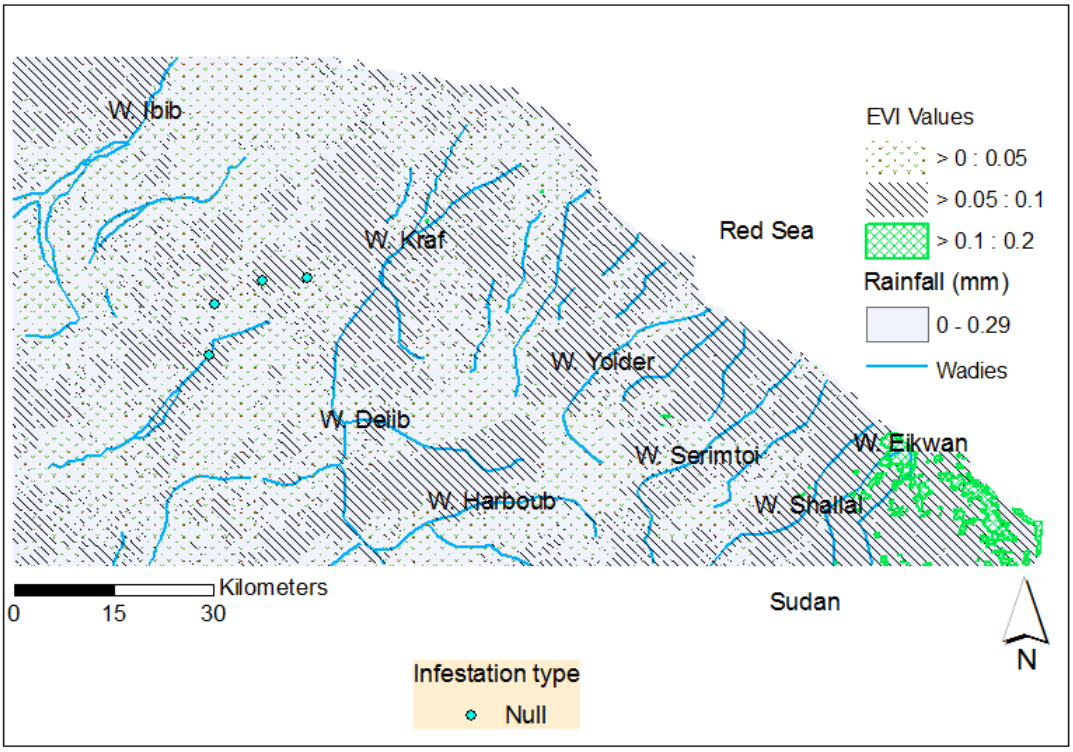


Figure 21: Rainfall, vegetation and infestations in January 2007

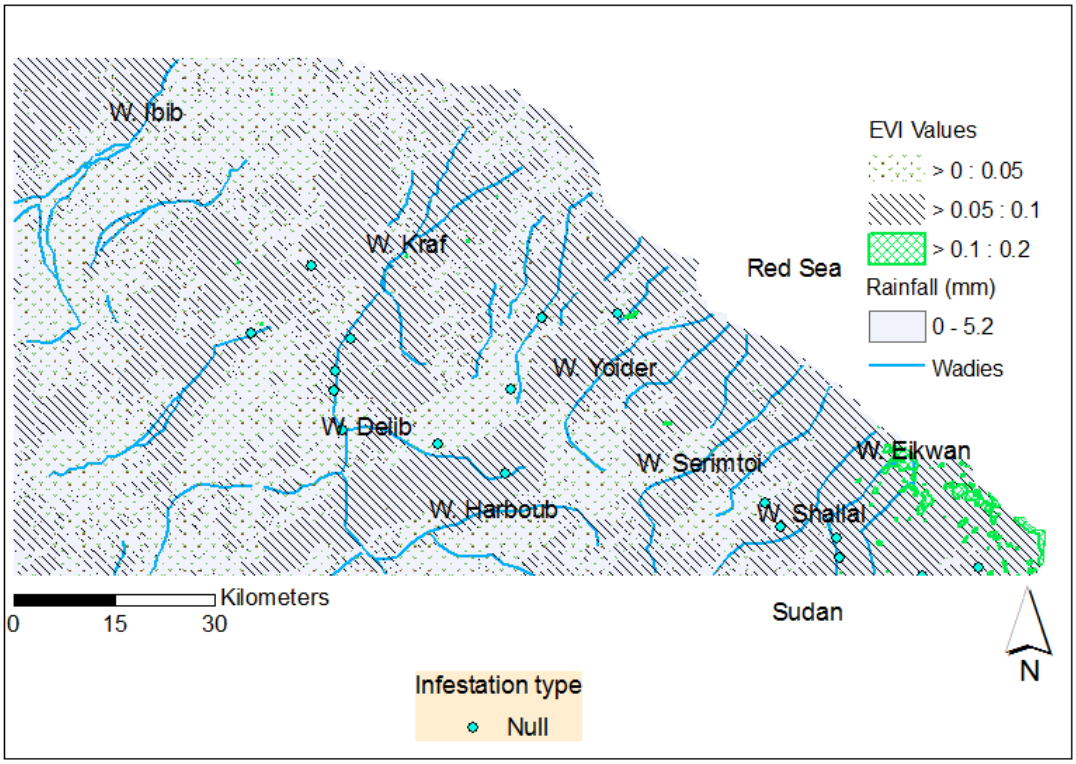


Figure 22: Rainfall, vegetation and infestations in February 2007

In March 2007, light rainfall occurred, the EVI decreased in the range > 0.1 to 0.2, and there were solitary adults in Shallal and Eikwan wadies, within the EVI range > 0.05 to 0.1 (Figure 23). This might have occurred because of the migration of some adult insects from the winter breeding areas in the north of Sudan (FAO, 2007b).

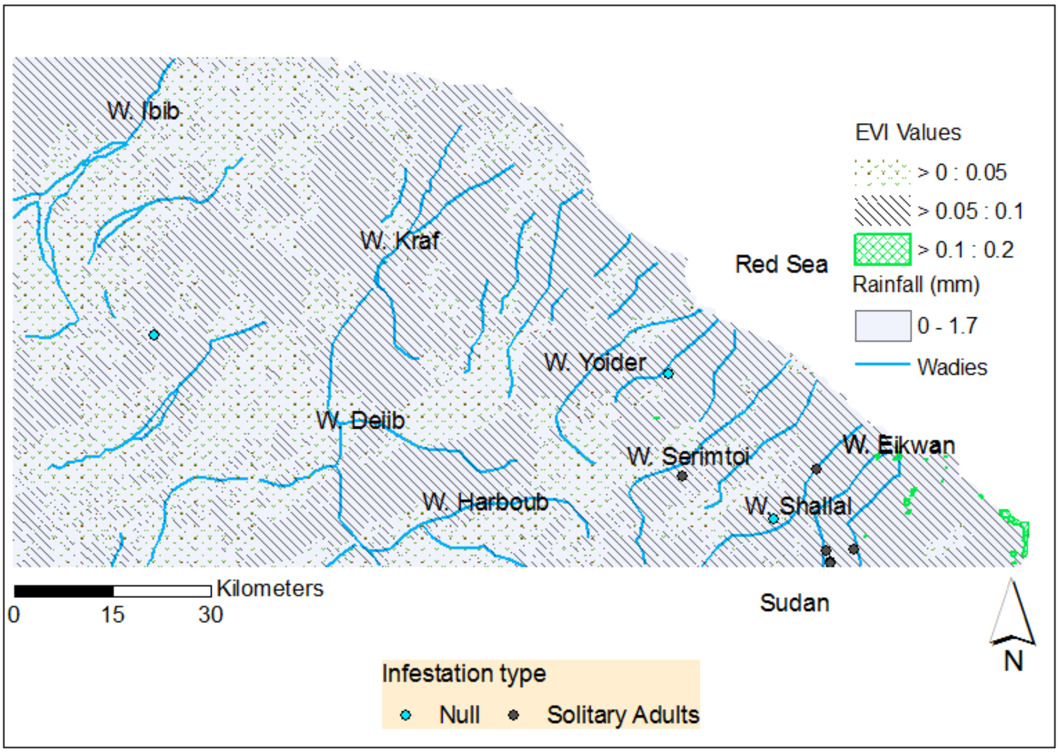


Figure 23: Rainfall, vegetation and infestations in March 2007

- **The winter season of 2007/2008**

Very light rainfall occurred in the early season; it increased slightly in the mid season, and decreased again at the end of the season. The vegetation conditions varied across the season months, as EVI values were low firstly, improved slightly at the mid season and decreased again in the late season. The infestations were characterized by the presence of solitary adults which were low in number in most of the season months (Figures 24 to 29).

Figure 24 below shows a very light rainfall that occurred in October 2007, and the EVI values decreased in the range of > 0.1 to 0.2. The solitary adult insects were found in Deiib and Yoider wadies, within the EVI range of > 0.05 to 0.1. These infestations might have occurred due to the migration of the solitary and gregarious adults from the Deiib wadi of Sudan during October 2007 (FAO, 2007b). This part of Deiib wadi in Sudan also had infestations with the late instars hoppers and fledglings during November 2007 (FAO, 2007b, c). These infestations might have developed into solitary adults in Deiib wadi in Egypt in November 2007, during which traces of rainfall occurred. In addition, the EVI values improved slightly in the range of > 0.1 to 0.2. The solitary adults of the desert locusts were found in Deiib, Harboub and Yoider wadies in the EVI range of 0.05 to 0.2 (Figure 25).

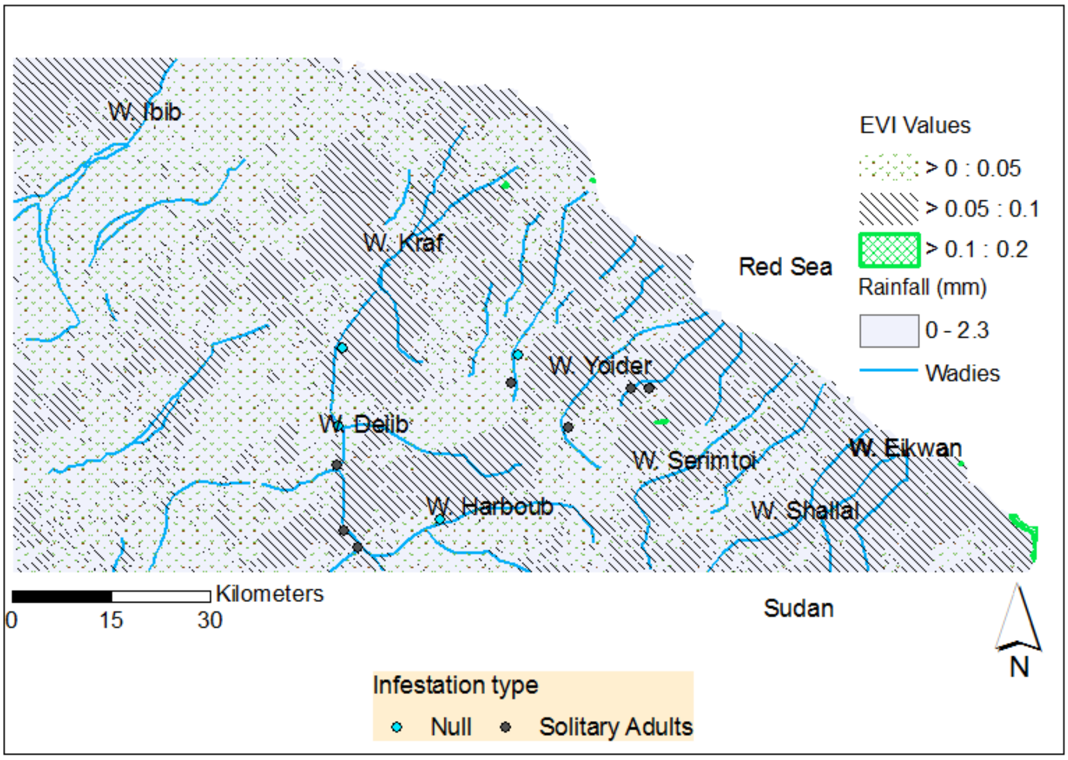


Figure 24: Rainfall, vegetation and infestations in October 2007

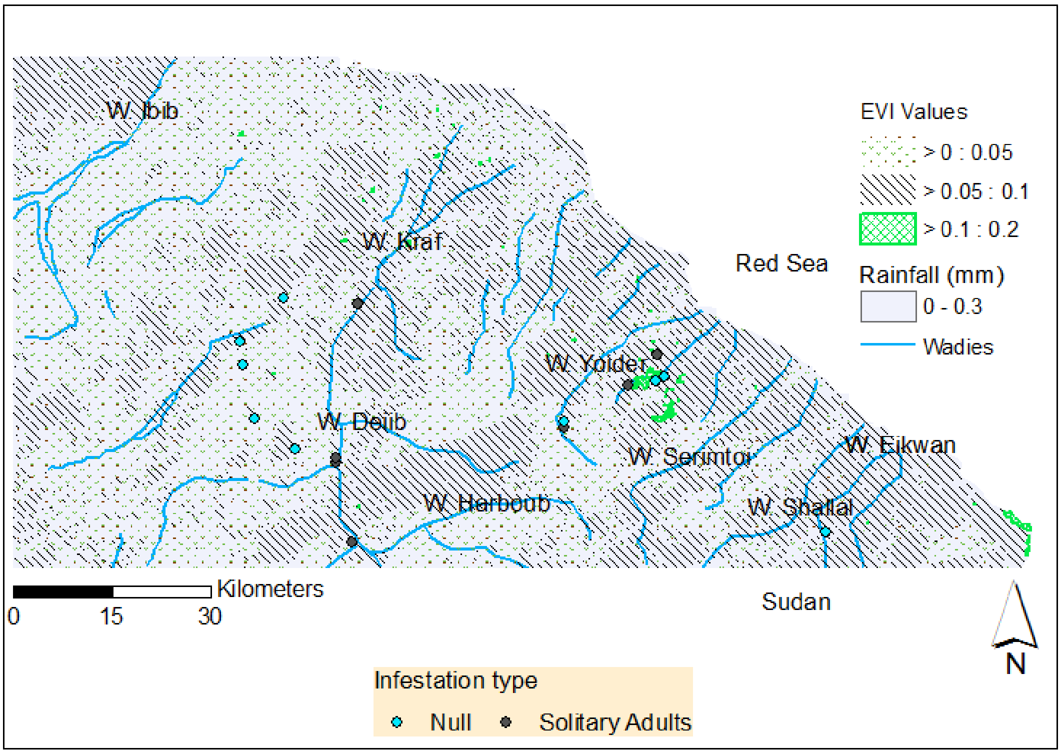


Figure 25: Rainfall, vegetation and infestations in November 2007

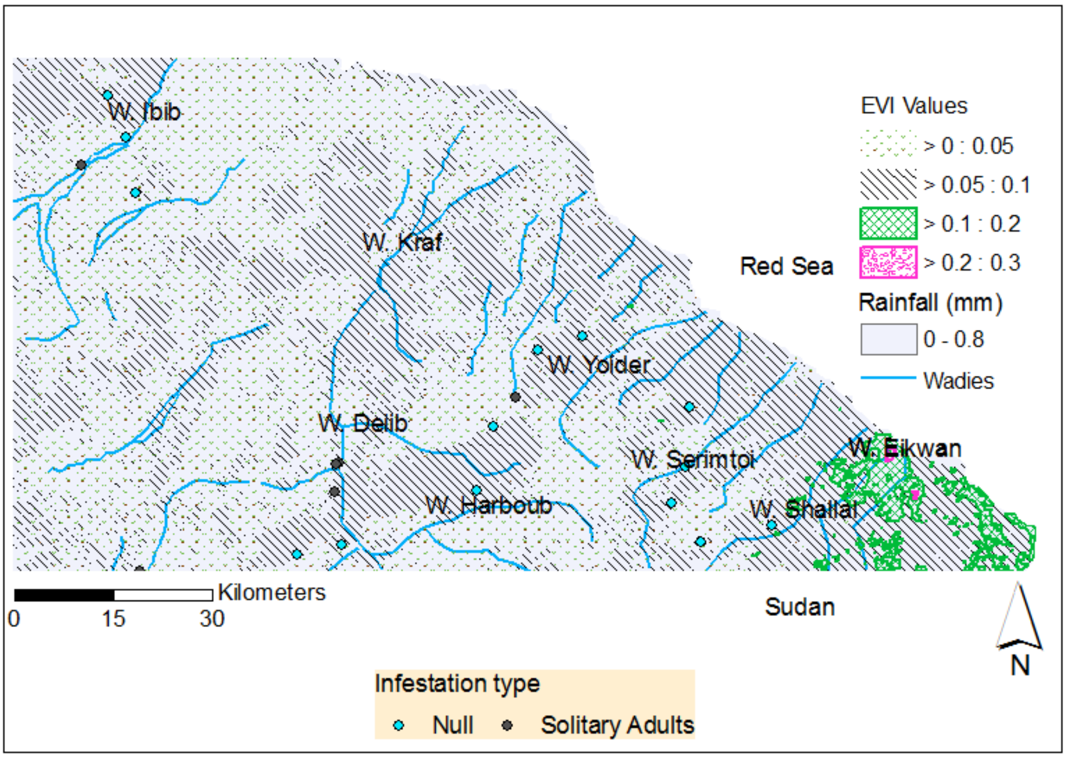


Figure 26: Rainfall, vegetation and infestations in December 2007

Figure 26 above shows that the traces of rainfall occurred in the study area in December 2007, with less than 1 millimeter. While, the EVI value increased in the ranges of > 0.1 to 0.2 and increased slightly in the range of > 0.2 to 0.3 in the south east part of the area. Solitary adults were found in Ibib, Yoider and Deiib wadies, in the EVI range of > 0.05 to 0.1.

The infestations continued in January 2008, but they were restricted to Deiib wadi, as the vegetation started to dry up in the area (Figure 27). A limited breeding was believed to occur by mid-January 2008 in the study area, due to the presence of these adult insects, and the occurrence of light rainfall (FAO, 2007b, c). The dry vegetation condition might have resulted from the less favourable conditions along both the eastern and western Red Sea coasts (FAO, 2008a).

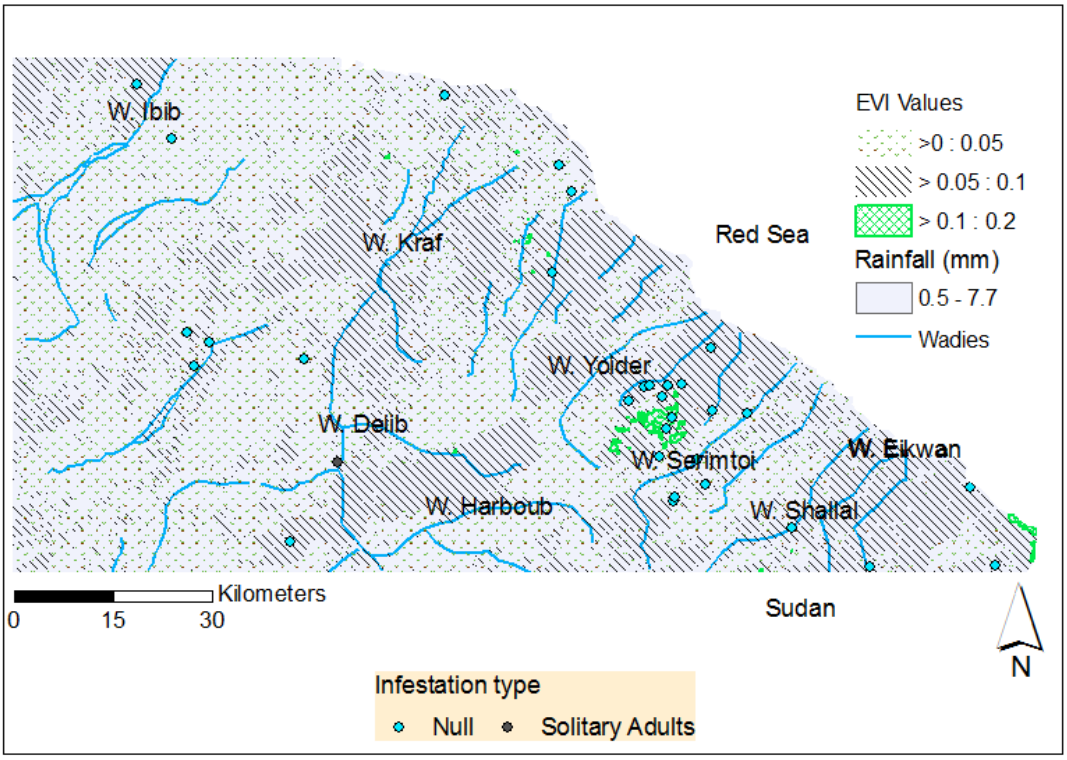


Figure 27: Rainfall, vegetation and infestations in January 2008

It can be noticed from figure 27 that many survey stops were made in the east area within and around the EVI values of > 0.1 to 0.2, as the surveyors might have tried to search many times in this part to look for the infestations. The figure also indicates that the light rainfall occurred 7.7 millimeters in the area. The EVI decreased in the range of > 0.1 to 0.2. The infestation was restricted to small area in Deiib wadi.

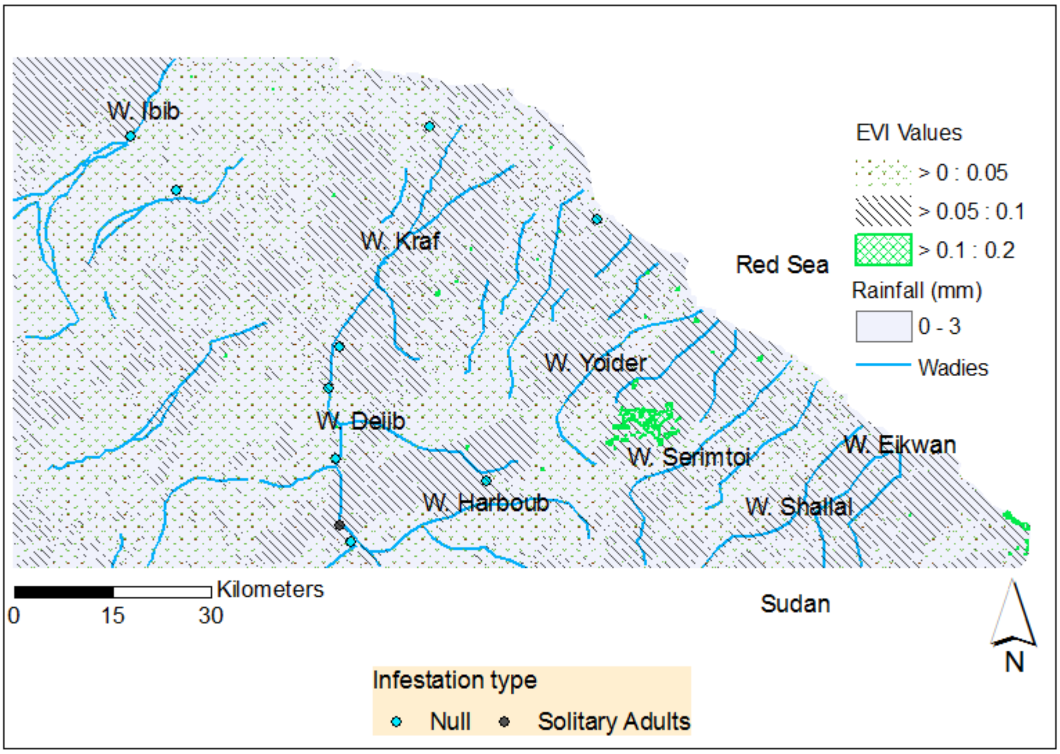


Figure 28: Rainfall, vegetation and infestations in February 2008

In February 2008, light rainfall occurred with a maximum of 3 millimeters, and there were no radical change in the EVI value. Infestations by solitary adults were in Deiib wadi, in the EVI range of > 0.05 to 0.1(Figure 28). In March 2008, no infestations were found and a very light rainfall occurred during it, while the EVI improved slightly in the range of > 0.05 to 0.1, but decreased in the range of > 0.1 to 0.2 (Figure 29).

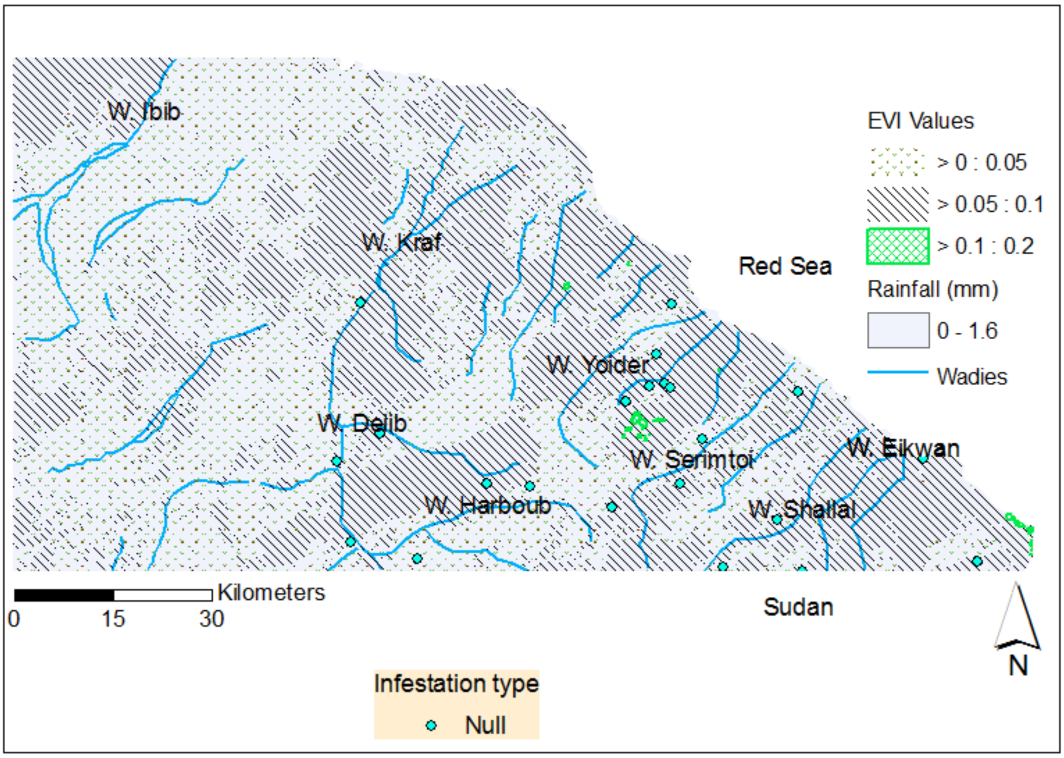


Figure 29: Rainfall, vegetation and infestations in March 2008

- **Summary for the effect of rainfall and vegetation on the desert locust**

1- It can be noticed from the above overview of the results that the highest infestations and breeding occurred in the first winter season (2004/2005), as it was characterized by widespread and heavy rainfall which supported the green vegetation growth; the food source for the desert locusts. In addition, the rainfall provided the required soil moisture for breeding to occur, as the egg development occurs when there is suitable moisture content in the soil. Moreover, there was an outbreak in most countries of the recession area at that time and this led the infestations to spread and increase in the study area.

2- There were no infestations at all in the second season (2005 / 2006); this can be either due to the dry conditions of the rainfall and vegetation, or because the survey teams did not make the best search for finding the infestations.

3- The occurrences of infestations were noticed mainly in the wadies, as they have the favourable habitat conditions for the desert locust. In addition, the rainfall water runs from other areas to the low lands of the wadies. Furthermore, vegetation in the wadies provides the food and shelter for the insects. Therefore, the survey teams conduct surveys in the wadies and the plain areas with similar characteristics.

4- Deiib wadi is the area where most infestations occurred, as it is a suitable habitat for the desert locust breeding and it receives many amounts of rainwater from its parts, which extend from the north of Sudan to the study area.

5- The visual interpretation for the above maps showed that infestations occurred mainly within the EVI value range of > 0.05 to 0.2. In order to confirm this observation, a spatial join was run for the monthly infestations and the monthly EVI layers (after converting them to vector layers), and the results are provided in Table 1 below.

Table 1: The size of infestations in hectares found within each EVI value range

EVI Range	Average vegetation area (hectares)	Average infested area (hectares)	Percent of the infested vegetation area
≤ 0.05	297165	40.2	0.014 %
> 0.05 to 0.1	341565	1794.4	0.53 %
> 0.1 to 0.2	1521	365	24 %
> 0.2	8	0	0 %

(Note: the table shows the average vegetation areas across the months of the infestations, and the average infested areas which occurred during these months)

It can be noticed from table 1, that most infestations (1794.4 hectares) occurred within the EVI range of > 0.05 to 0.1, but they represent about 0.53% of the average vegetation area in this range. Whereas, 365 infested hectares were found within the EVI range of > 0.1 to 0.2, representing 24 % of the vegetation area in this range. While, only 40.2 hectares of infestations occurred within the EVI range of ≤ 0.05, representing 0.014 % of the vegetation area in this range. In addition; no infestations were found within the EVI values of > 0.2.

The reasons for the infestations to occur mainly within the range of > 0.05 to 0.2, which is low EVI value can be either that the egg laying by the desert locust females occur in a bare ground of sandy soil with low green vegetation density, as it was mentioned in section 2.4., or that the preferred plants for the desert locust can be found within this EVI range.

Based on this result, more infestations are predicted to occur in the EVI of > 0.1 to 0.2. However, the value of > 0.05 to 0.1 contained very large sizes of infestations which can cause problems if ignored, so that it was measured as a part of the likely infested and breeding areas. Then, the survey teams can be targeted to carry out the surveys within vegetation areas within the EVI value range of > 0.05 to 0.2 (which may vary from one month to another). This is recommended after demarcating the vegetation extent (by processing the EVI layers using the GIS software), and providing the survey teams with a boundary map concerning the suitable areas to be surveyed.

4.1.2. The Relationship between the Elevation Level and the Desert Locust

Figure 30 shows the elevation levels in the area, which vary greatly from less than 200 meters in the coastal areas (the yellow colored parts), while it is high in the south western parts and the middle south areas (the dark brown colored areas) which represent the mountains and hills.

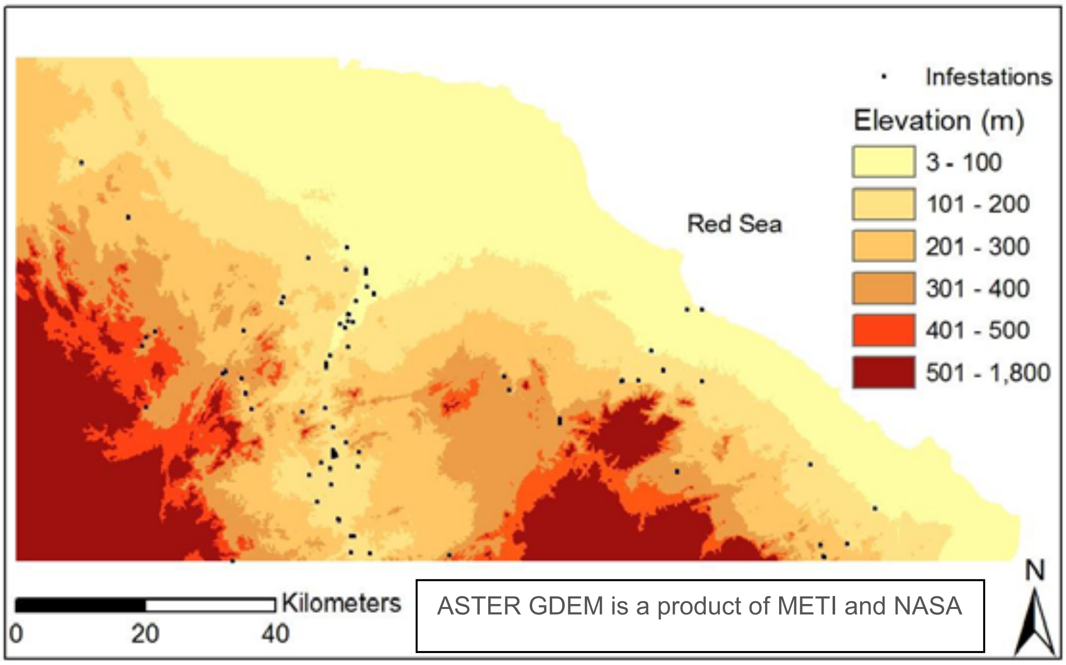


Figure 30: Infestations by desert locusts within the various elevation levels

The above figure shows that all infestations by the desert locust occurred at the elevation level of < 400 meters. In order to confirm this observation, a spatial join was applied between the sites of the infestations and a vector layer, which was created by converting the raster DEM layer into a vector one (Figure 31).

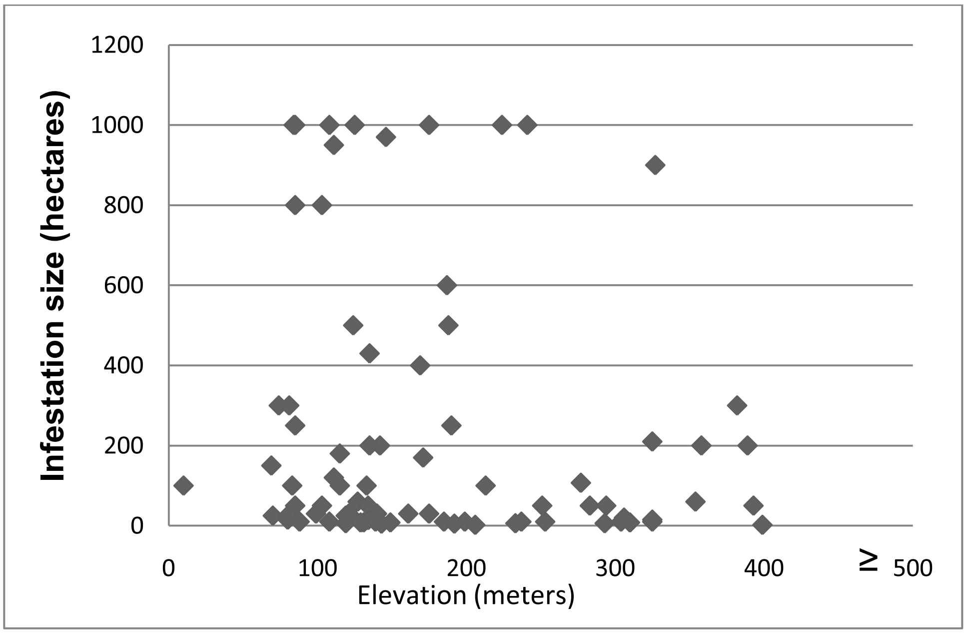


Figure 31: Elevation levels and the desert locust infestation sizes

Figure (31) above confirms that all the infestations occurred at the elevation level of less than 400 meters. The infestations mostly occurred at this elevation level for many reasons:

1- The areas at this level (which include the wadies and the plains) contain the sandy soils which are suitable for the desert locust breeding while the higher elevation levels are mostly hills and mountains (rocky areas) which are non-suitable for breeding.
2- One can surmise that the vegetation species, which are the food source and shelter for the desert locust, are found at this elevation level in this area.

- **Third: The relationship between the rainfall and vegetation growth**

The vegetation areas in the EVI range of > 0.05 to 0.2 (which represent the likely infested area), and the rainfall areas were estimated in a rectangular area (contained within the study area) that comprises 6 complete rainfall grids (Figures 32 and 33).

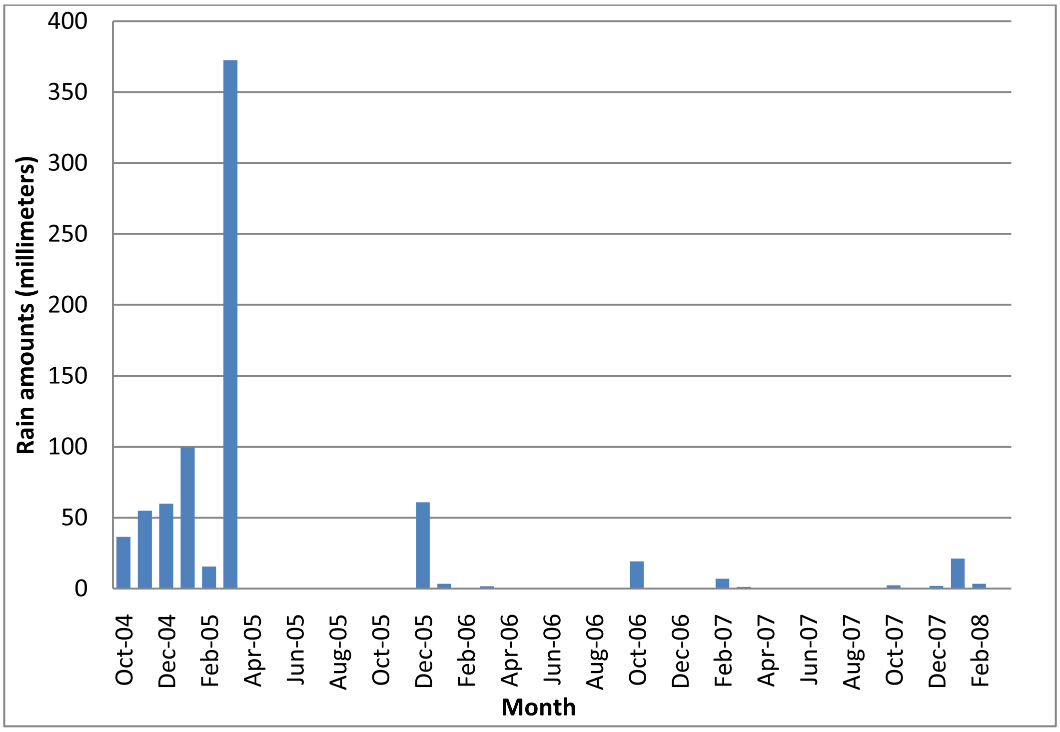


Figure 32: Total rainfall amounts across the winter seasons 2004-2008

Figure (32) above shows that the rainfall varied greatly across the months of the four winter seasons in the selected location in the study area; however, it was the heaviest in the first year. Figure 33 shows the vegetation areas within the EVI values of > 0.05 to 0.2, for the same months and in the same area where the rainfall was estimated. The chart shows that the green vegetation areas in the first winter season of 2004/2005 were larger than the vegetation areas in the next seasons. However, they were not greatly smaller in the next seasons.

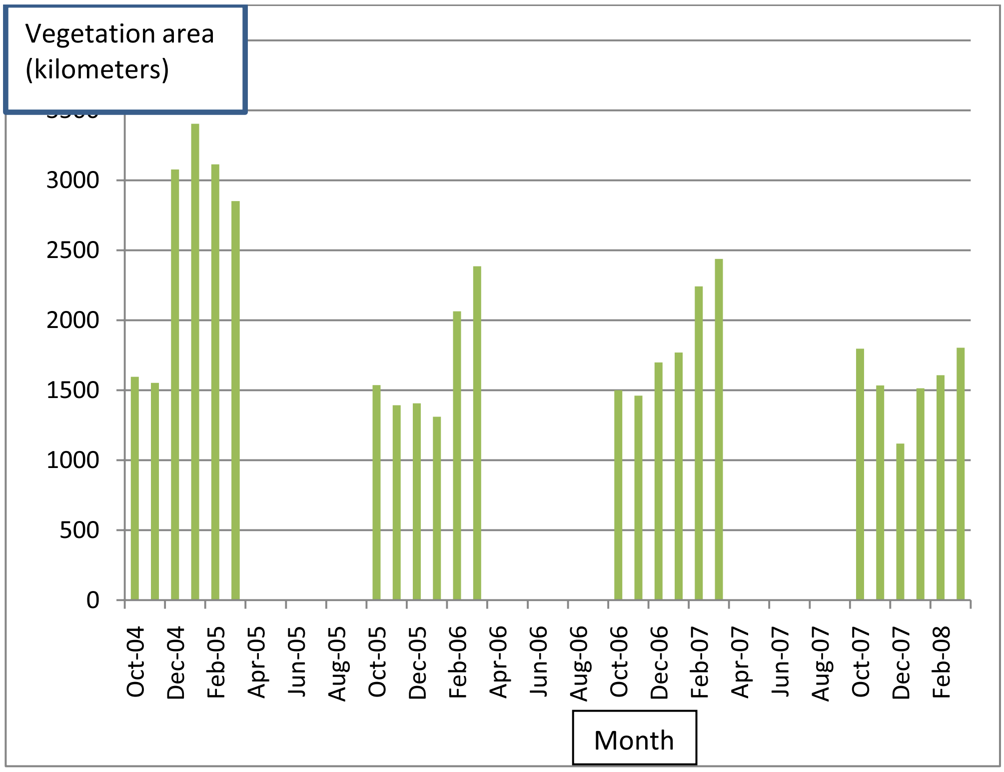


Figure 33: Vegetation areas across the months of the four winter seasons

The statistical relationship between the green vegetation areas within the EVI values of > 0.05 to 0.2 was investigated via the regression analysis using the SPSS 18 software (Figure 34). The analysis results showed that there is a linear relationship between the rainfall and vegetation growth; the r square interprets 19.4 % change in the vegetation area due to the effect of rainfall change, and T value is 2.3 at significance of 0.03.

The r square and T values are not high, which means that the relationship is not very strong. This can be attributed to the fact that some vegetation areas are permanently green, as they receive ground water, and other vegetation areas in wadies, such as Deeib, receive running water from its parts in the Sudan, so the vegetation areas will green-up devoid of the of rainfall in the study area. Moreover, rainfall might have occurred at the end of some months and the vegetation grew in the next months, which might had not any rainfall.

Furthermore, the statistical analysis depended on the data derived from the processing of the remote sensing images of the rainfall and EVI, which might not be so accurate due to the factors affecting the remote sensing imagery. These factors include the sensor, the energy source and energy matters interactions at the earth's surface. For example different material types can have great spectral similarity making their differentiation difficult. Also, no single sensor is sensitive to all wavelengths and all sensors have fixed limits of spectral sensitivity (Lillesand, Kiefer and Chapman, 2008). Besides, the rainfall data are subject to a random error which affects their accuracy (Huffman, 1997). All of these reasons can cause the analysis results to indicate less strong relationship between rainfall amounts and vegetation growth.

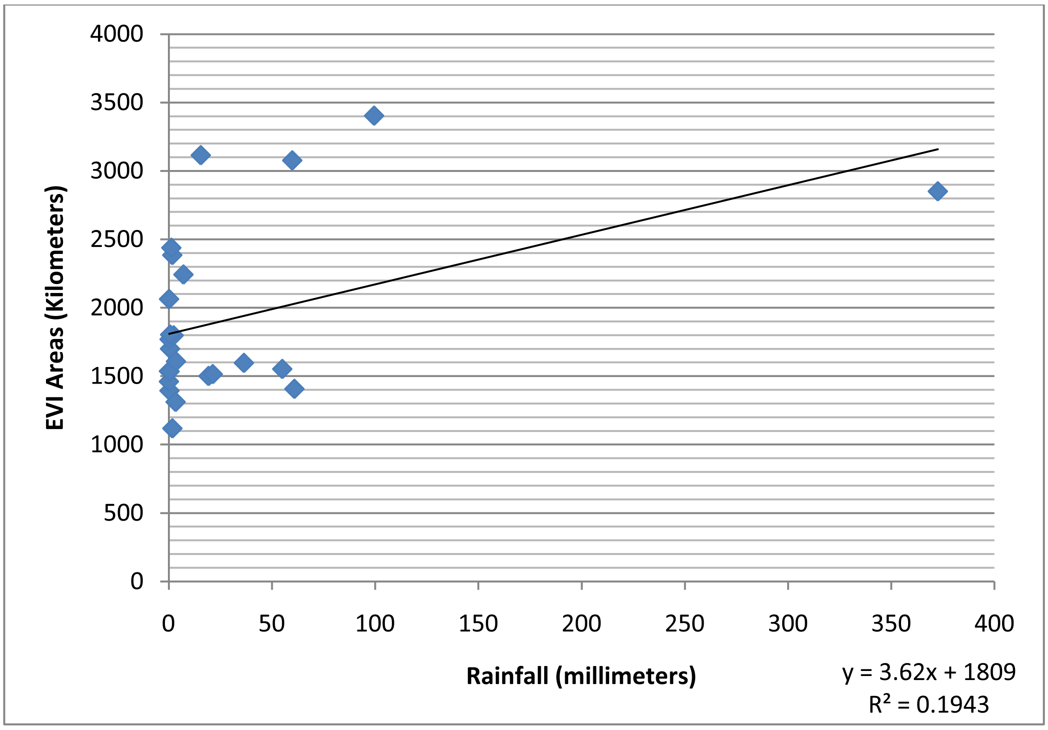


Figure 34: The relationship between the monthly rainfall and the vegetation areas within the EVI range of > 0.05 to 0.2.

According to the formulae in the above chart, if rainfall (x) was 100 millimeters, then the vegetation area in the > 0.05 to 0.2 EVI range (y) would be (3.62*100+1809); which equals 2171 square kilometers.

4.2. Estimation of the Likely Breeding and the Likely Infested Areas (Results of section 3.4.2)

It should be noted that the estimation of the likely infested and breeding areas in this thesis represents the areas, within which infestations might occur during the periods of increased locust activity. The estimation depended on calculating the vegetation areas found within the EVI range of > 0.05 to 0.2 and in the elevation level of < 400 meters. This is based on the EVI value and the elevation level within which the infestations occur mainly in repetitive manners, as it was seen from the above results.

The difference between the likely breeding and the likely infested areas is that, the likely breeding areas are sandy soil areas, which received good rainfall recently. In addition, the areas covered by rocky feature, such as the mountains and hills, which are non-suitable for locust breeding are excluded from the vegetation areas. Unfortunately, there is no accurate copy of the digital or scanned map to be used for estimating the areas covered by these rocky features in the study area. So, the likely breeding areas will be estimated equally to the likely infested area.

The blue area in Figure 35 below, shows the boundary of the area with elevation lower than 400 meters, while Figure 36 shows estimations of the likely breeding and likely infested areas within this boundary (in square kilometers), across the months of the four winter seasons of 2004-2008.

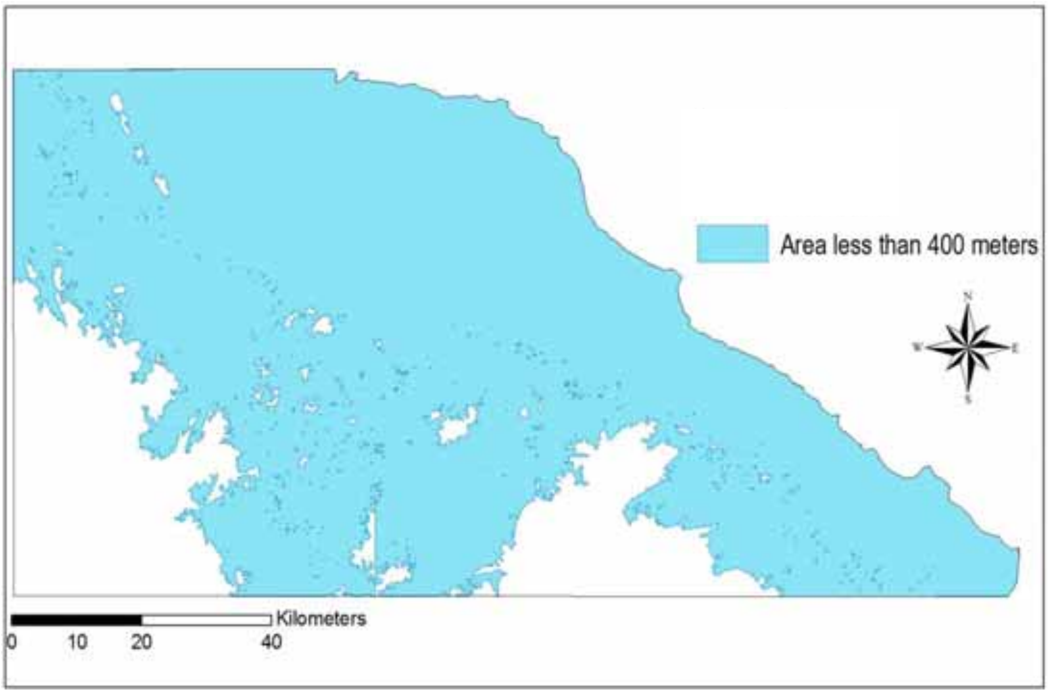


Figure 35: The boundary of area with less elevation levels than 400 meters

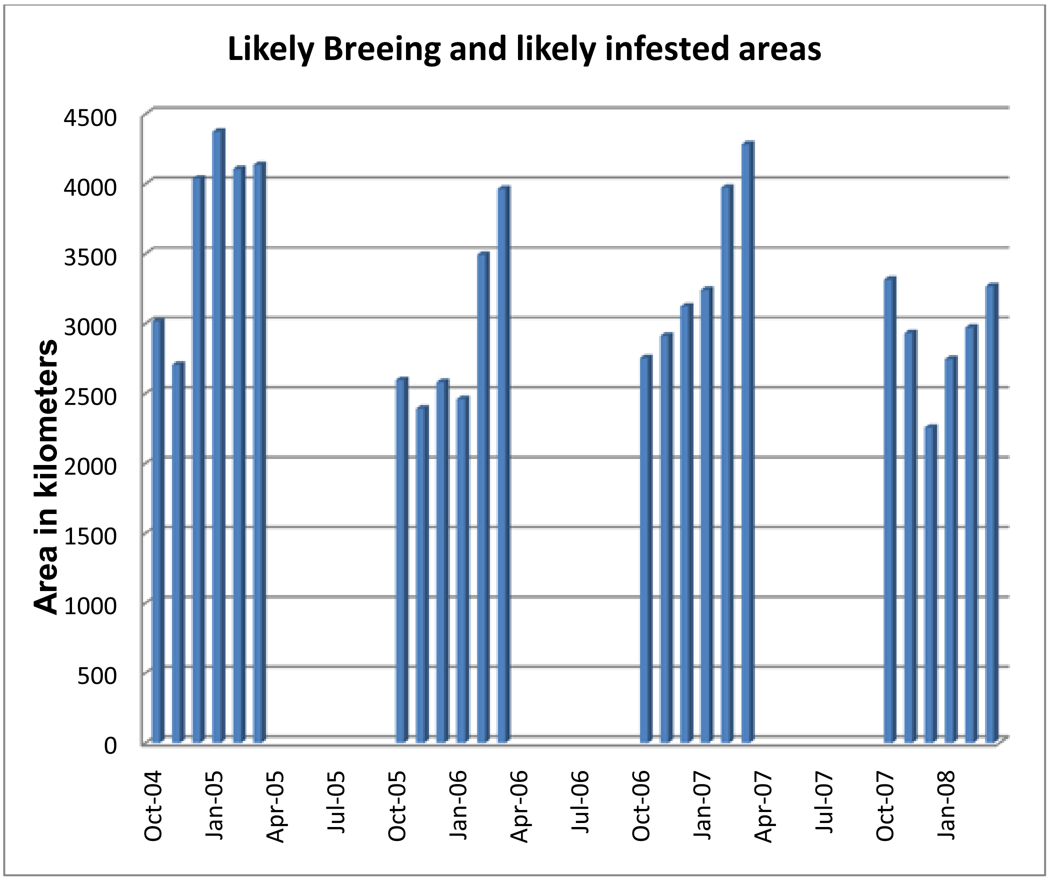


Figure 36: The estimated likely infested and likely breeding areas across the four winter seasons in lower elevation level than 400 meters

4.3. Measuring the Infested Area and Spatial Dependency of the Desert Locust by Kriging (Results of section 3.4.3)

Kriging was performed using survey data of each 3 months, as the monthly data were not enough to run the analysis. However; January, February and March 2005 contained enough data for running the kriging separately. The vegetation maps for the average EVI values were also produced (for each period with the kriged maps), to compare the size of predicted infestations with the EVI value in the same locations. The cell size (lag size) used for kriging is provided in table 2, page 81 (Cell size was larger than the predicted infestation size in all the periods).

The semivariogram measures the spatial autocorrelation between the measured infestation points across the vegetation areas. It relates the dissimilarity of the data points to the distance which separates them. The spatial autocorrelation is indicated by the range, which marks the distance when the semivariogram line levels off. The flattening of the semivariogram indicates that there is little autocorrelation beyond the range (Johnston et al., 2001; *ESRI, no date).*

4.3.1. Kriging Prediction Maps

- **<u>First: Winter season of 2004 / 2005</u>**

The kriging prediction maps for the infested areas of the desert locust in the early season of 2004 / 2005 indicate that the largest infested area (100 hectares) is found in the east of the study area, where there is a suitable average EVI value of > 0.05 to 0.1. However, some infested areas are predicted in lower EVI values (Figure 37). In January 2005 large infested areas of 1000 hectares were along the Deiib wadi where a suitable EVI range was also available (> 0.05 to 0.2), and smaller infested areas away from this wadi (Figure 38). In February 2005, the large infested areas of 1000 hectares were in Deiib and Ibib wadies, where a suitable EVI range was available (Figure 39). While, in March 2005, the infested areas were large (1000 hectares) in Deiib, Harboub and Kraf wadies with the suitable average EVI values of > 0.05 to 0.1 (Figure 40).

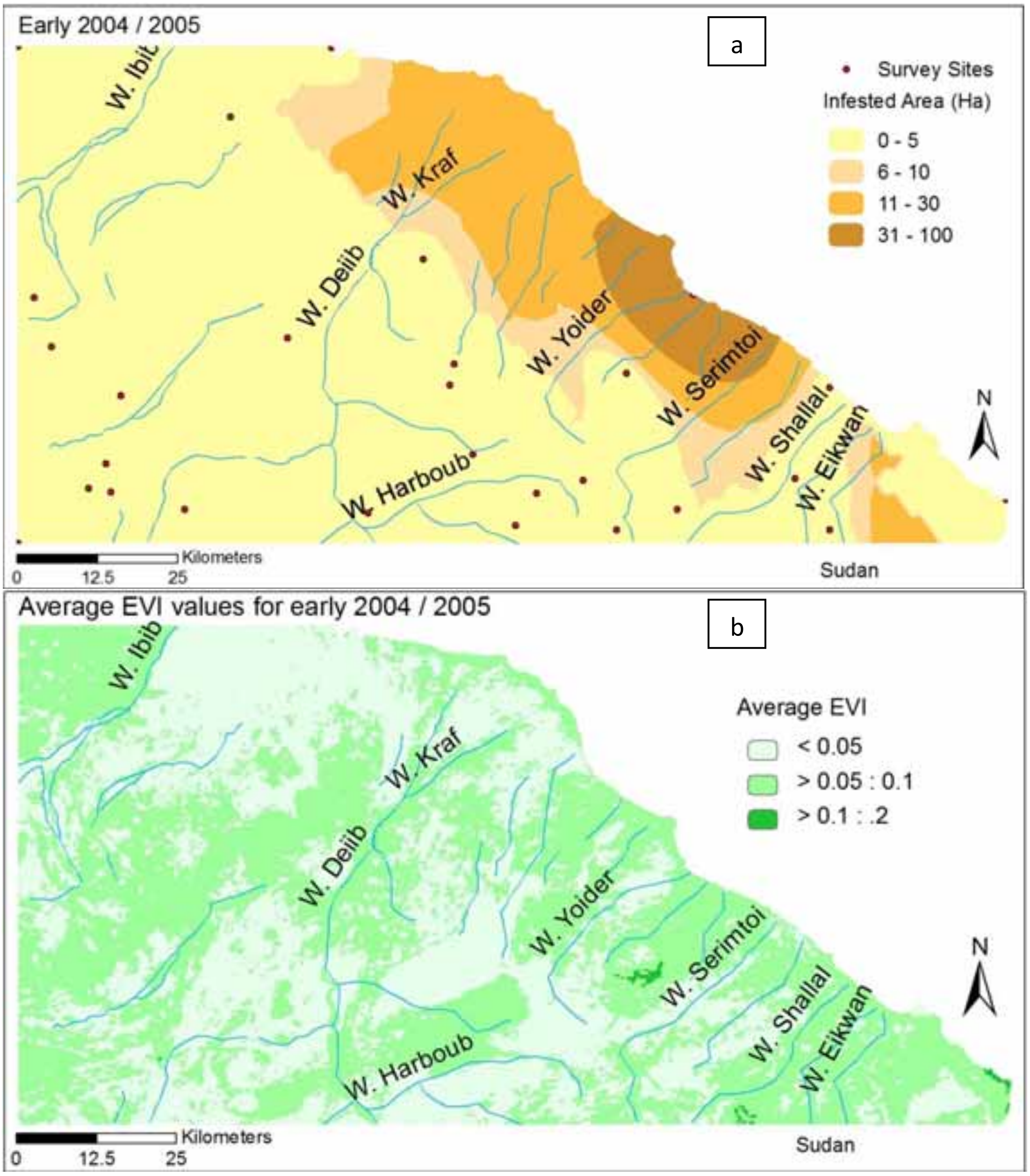


Figure 37: kriged map of the infestation sizes (a), and the average EVI values (b) in the early 2004 / 2005 winter season

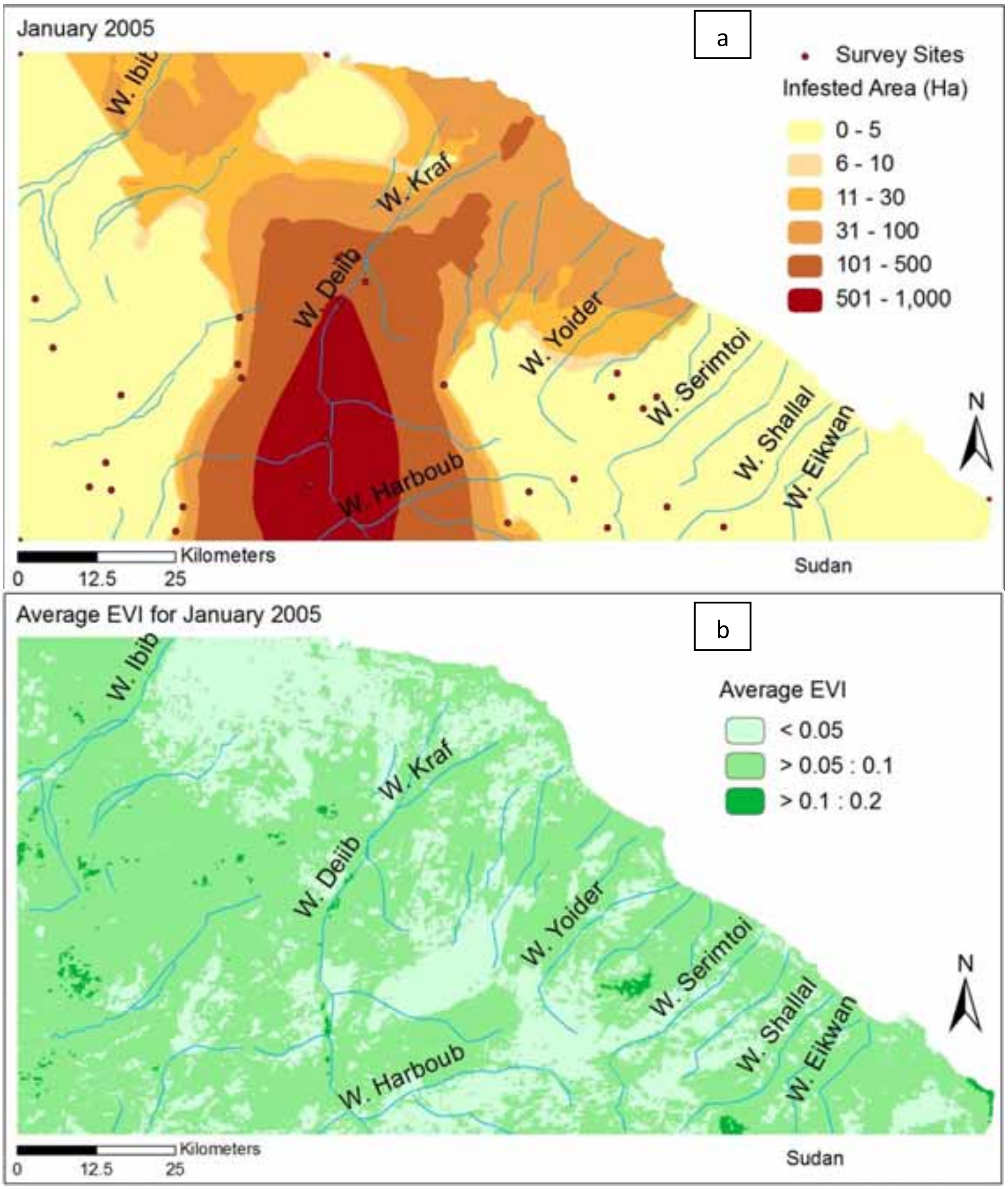


Figure 38: kriged map of the infestation sizes (a), and the average EVI values (b) in January 2005

It is noticed from the above and the following maps (Figures 37 to 44) that some predicted infested areas occurred in the EVI value of ≤ 0.05. This may be because the infestations originally occurred in the time when EVI values were suitable, but the average EVI was low due to the effect of averaging the original 16 days EVI values to get the average value in one month or in three months. In addition, some infestations occurred in lower EVI values, as in December 2007 in Ibib wadi (Figure 26), so they caused the prediction to be high.

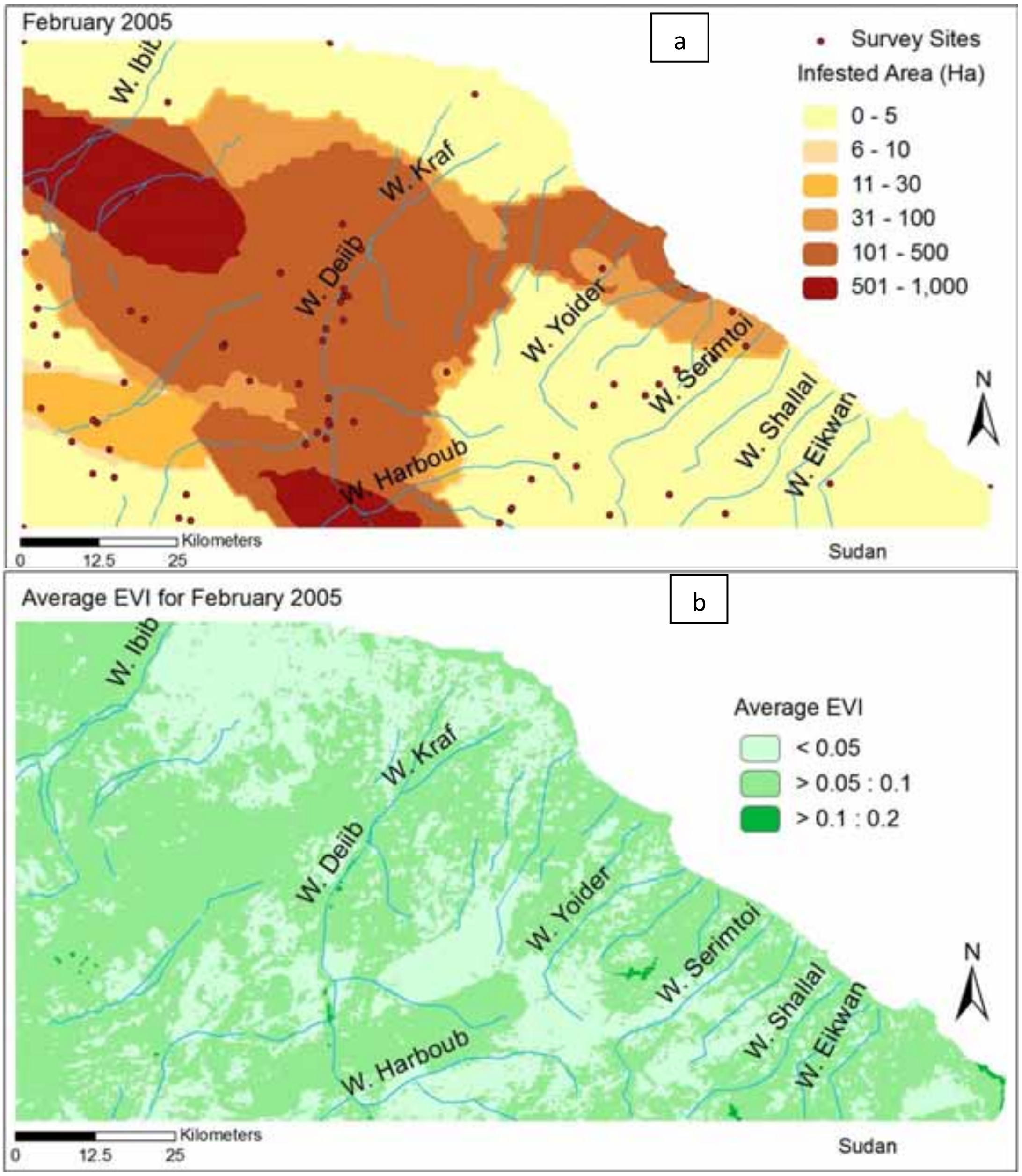


Figure 39: kriged map of the infestation sizes (a), and the average EVI values (b) in February 2005

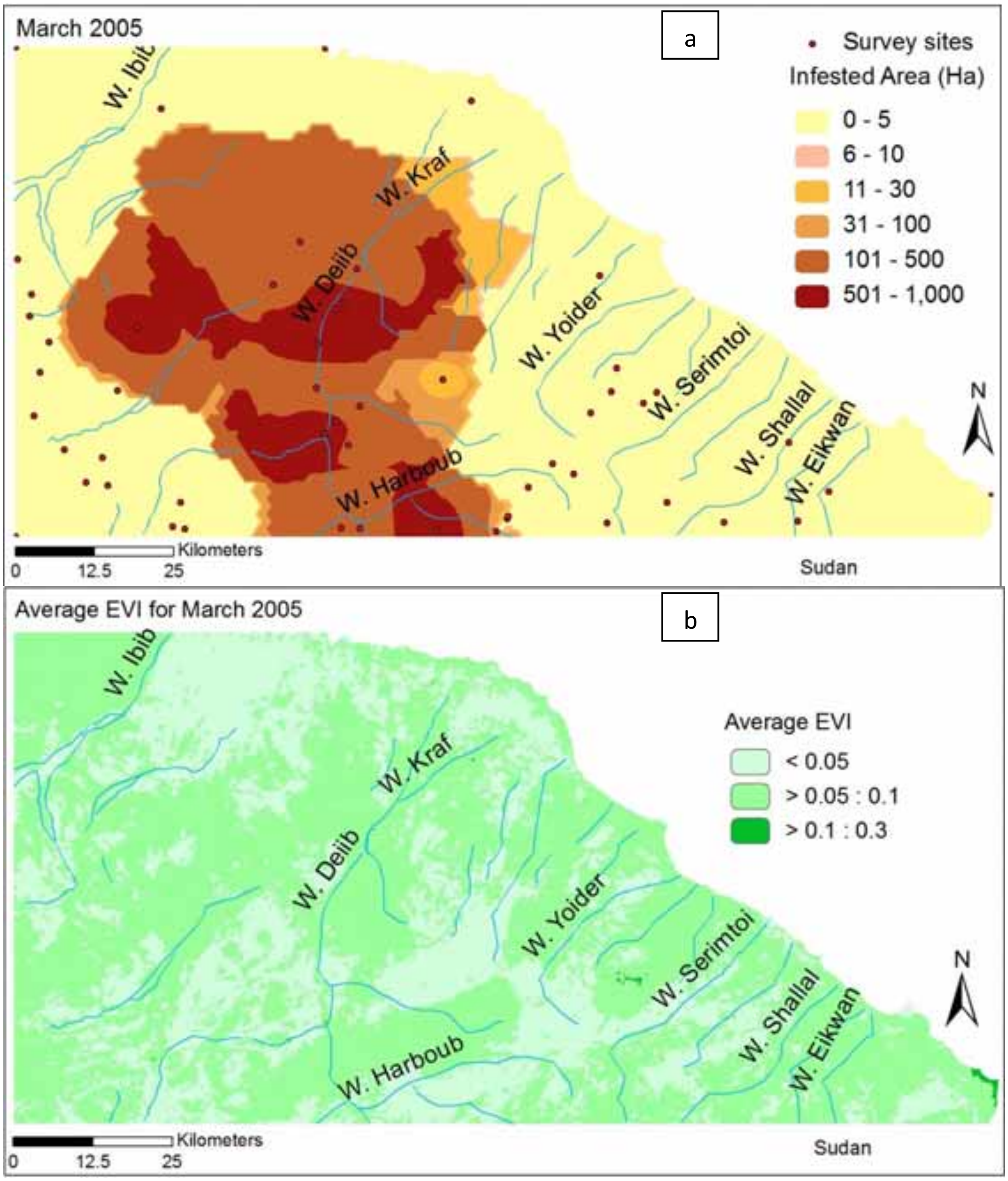


Figure 40: kriged map of the infestation sizes (a), and the average EVI values (b) in March 2005

- <u>Note: No infestations were found in the winter season 2005 / 2006</u>
- **<u>Second: Winter season of 2006 / 2007</u>**

The kriged maps for the winter season of 2006 / 2007 show that the largest infested areas were 11 to 30 hectares in Eikwan wadi within the suitable EVI value of > 0.05 to 0.2, and smaller areas around it as the EVI decreases (Figure 41). The infested areas in late 2006 /

2007 were 50 hectares beside the coastal areas where there were a suitable average of EVI values in the range > 0.05 to 0.1 (Figure 42).

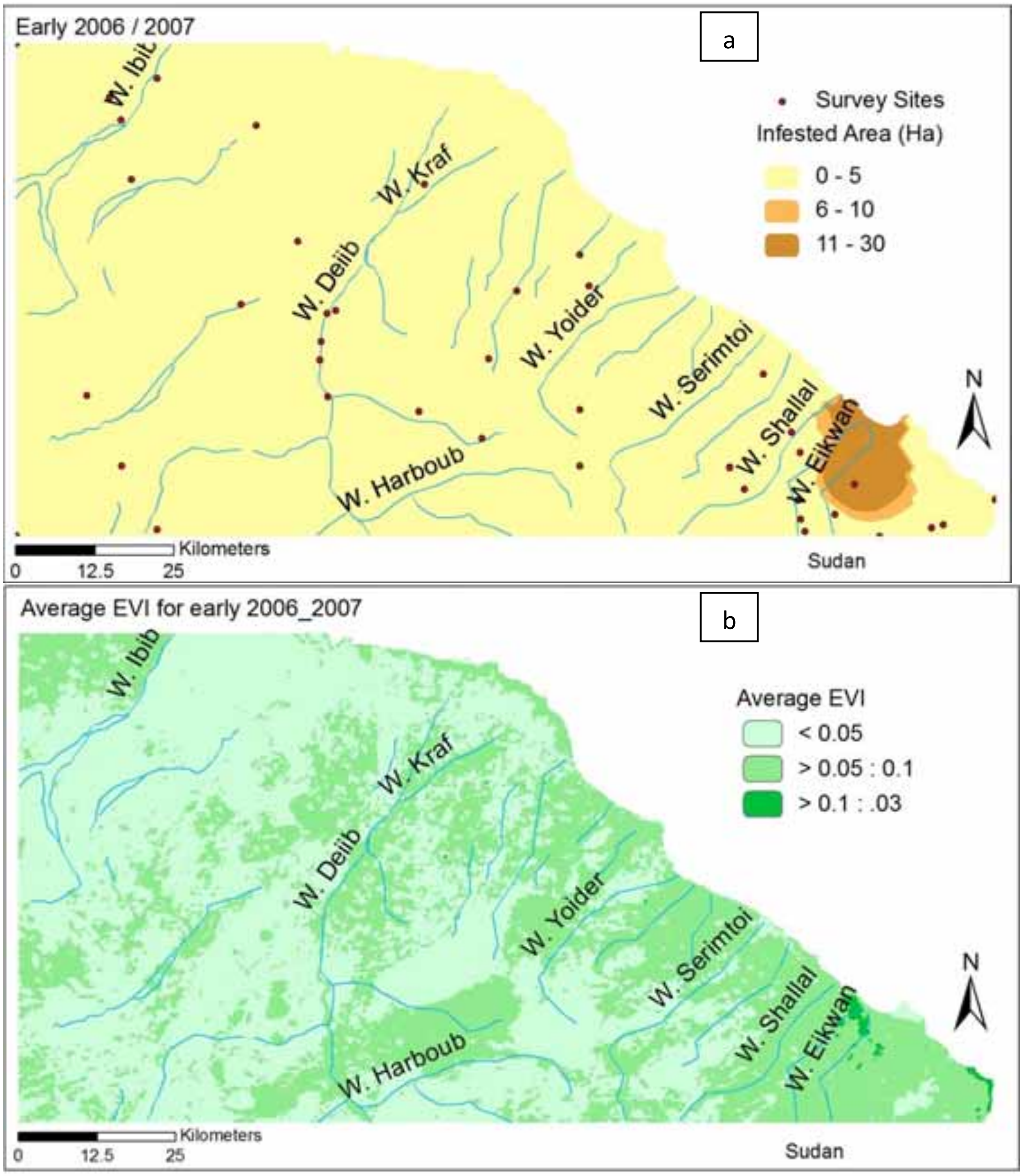


Figure 41: kriged map of the infestation sizes (a), and the average EVI values in the early 2006 / 2007 winter season

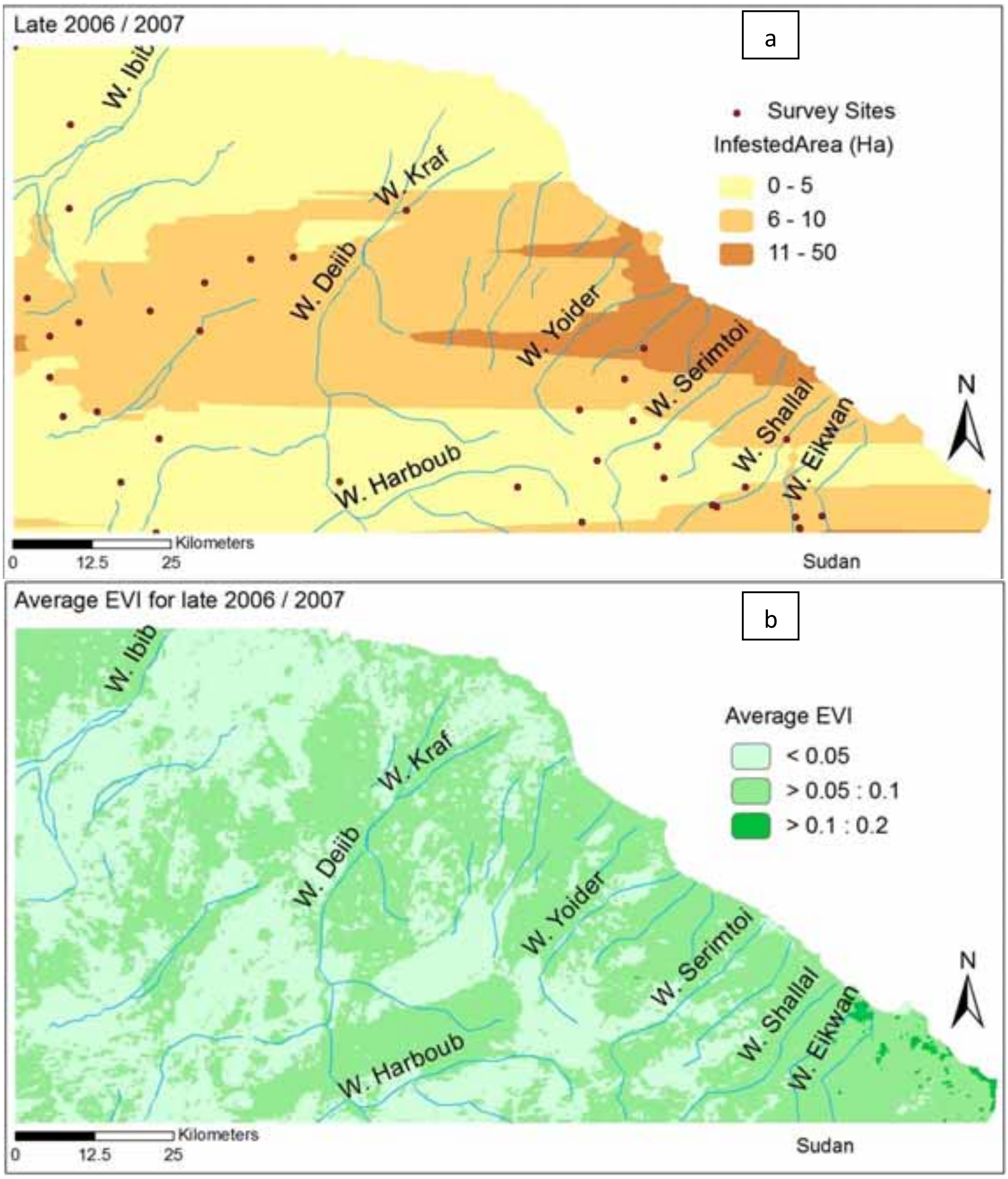
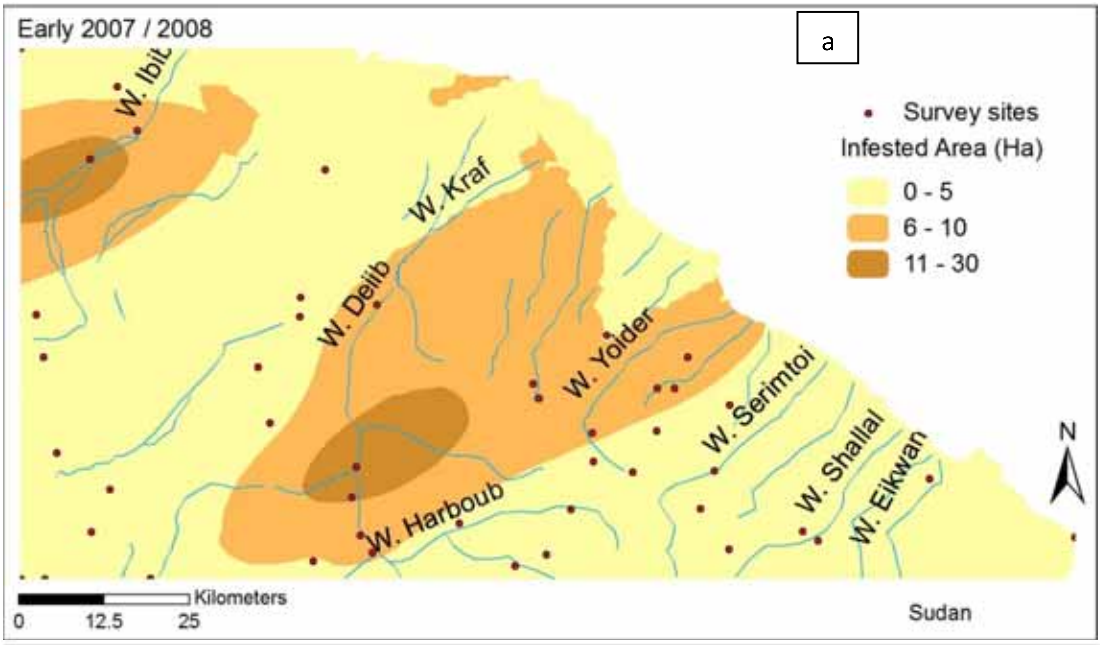


Figure 42: kriged map of the infestation sizes (a), and the average EVI values (b) in the late 2006 / 2007 winter season

<u>Third: Winter season of 2007 / 2008</u>

There were small infested areas with a maximum of 24 hectares across the Deiib and Ibib, wadies in the early 2007/2008, which had a suitable average EVI range of > 0.05 to 0.1 (Figure 43), though the EVI is lower in the infested parts to the north west of the area. In the late season, the infested area was very small, only 7 hectares in Deeib wadi (Figure 44).



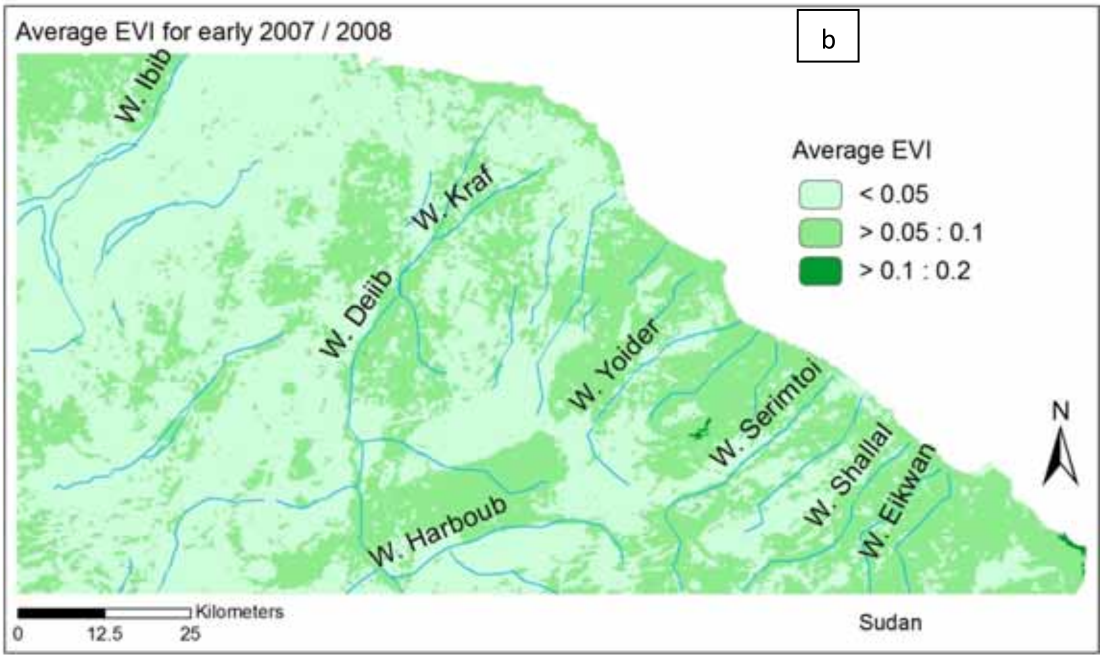


Figure 43: kriged maps of infestation sizes (a), and the average EVI values in the early 2007 / 2008 winter season

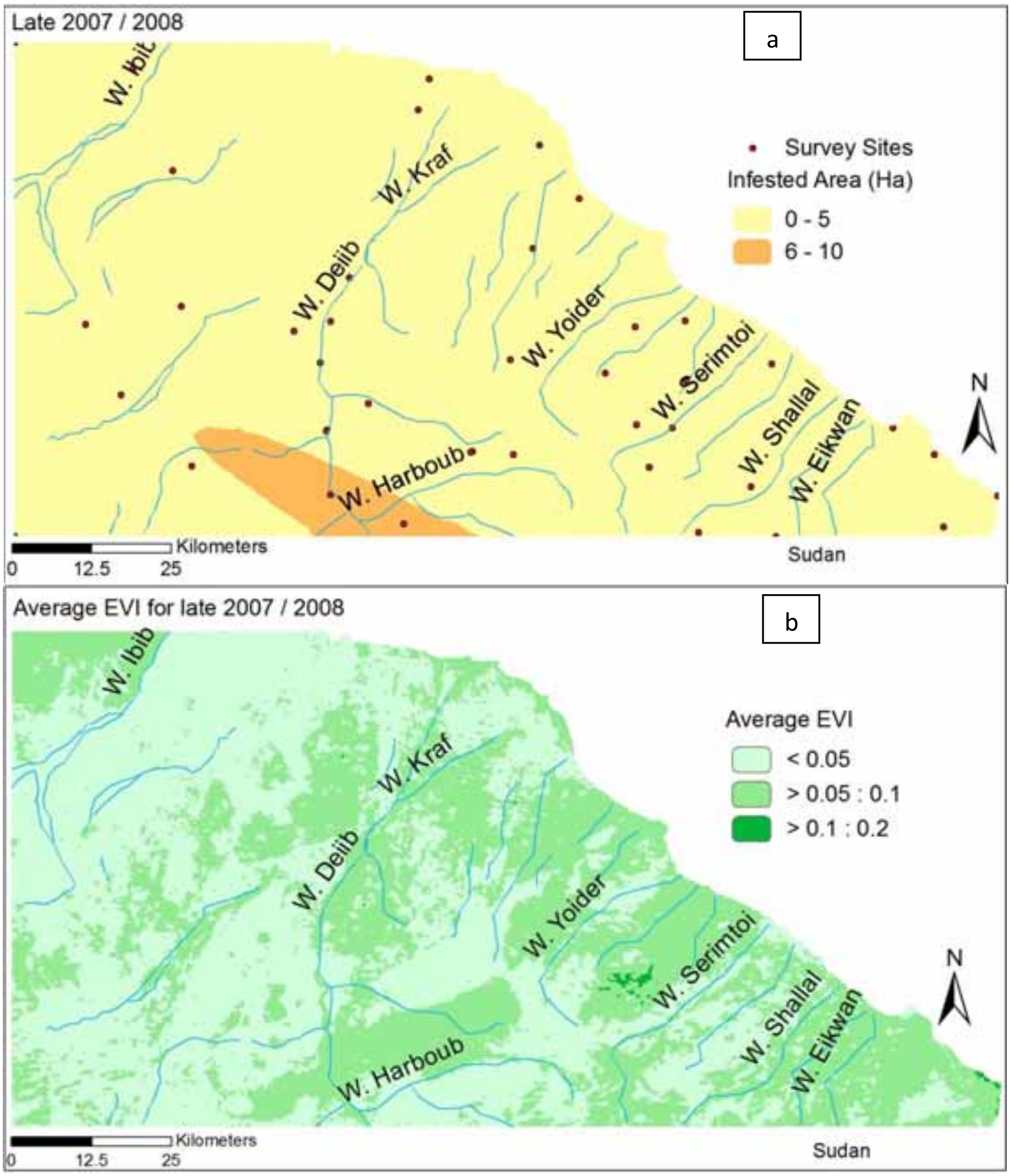


Figure 44: kriged map of infestation sizes (a), and the average EVI values in the late 2007 / 2008 winter season

- **<u>The usefulness of the kriging maps</u>**

Kriging prediction can be useful for making a decision after carrying out an assessment survey by surveying in few sites and estimating the infested areas within them. Then, these values are interpolated by kriging to see where the large infested sites are predicted. These sites will be the next surveys targets. This guarantees that most infestation hot spots can be found by the survey teams. In addition, the EVI values where large infestations are predicted can be used as guide for surveys to be conducted within them.

4.3.2. The Spatial Dependency of the Desert Locust Infestations

The spatial distribution of the desert locust and the vegetation correlation range was best described by the spherical model in all seasons (Table 2). In the early 2004/2005 winter season, the spatial dependency had a range of 0.17 decimal degrees (Figure 45 a), while in January, February and March 2005, the ranges were 0.29, 0.082, and 0.097 respectively (Figure 45 b, c, d). Whereas, the spatial dependency in early and late 2006/2007 winter season had a range of 0.083 and 0.18 decimal degrees respectively (Figure 46 a, b). Finally, in the early and late 2007/2008 winter season, the correlation ranges were 0.24 and 0.28 decimal degrees respectively (Figure 46 c, d).

The decrease in the range during February and March 2005 might have come as a result of the wide scale control operations, which were conducted in the study area against the gregarious desert locust, and then the correlation between the locust populations decreased. The shrink in the correlation of infestations in early 2006/2007, either might be due to the few infestation numbers or to the fact that there was shrinkage in the suitable vegetation area in early 2006/2007.

The correlation ranges found in this study for the desert locust infestations with the green vegetation (using EVI) in south east of Egypt, between 0.082 and 0.29 decimal degrees in the 2004-2008 winter seasons, are larger than those ranges of 5 to 24 kilometers found by Wlodewahid (2003) for the desert locust in north east Sudan in 1999/2000. The current ranges are also higher than those found by Rong et al. (2006) of 452 and 328 meters for the egg pods of the oriental migratory locust, in the years 2002 and 2003 respectively.

Table 2: The spatial dependency of the desert locust infestations across the four winter seasons

Winter season	Range (decimal degrees)	Lag size (square decimal degrees)
Early 2004 / 2005	0.17	0.025 (30250 hectares)
January 2005	0.29	0.033 (39930 hectares)
February 2005	0.082	0.015 (18150 hectares)
March 2005	0.097	0.016 (19360 hectares)
Early 2006 / 2007	0.083	0.01 (12100 hectares)
Late 2006 / 2007	0.18	0.12 (145200 hectares)
Early 2007 / 2008	0.24	0.058 (70180 hectares)
Late 2007 / 2008	0.28	0.115 (139150 hectares)

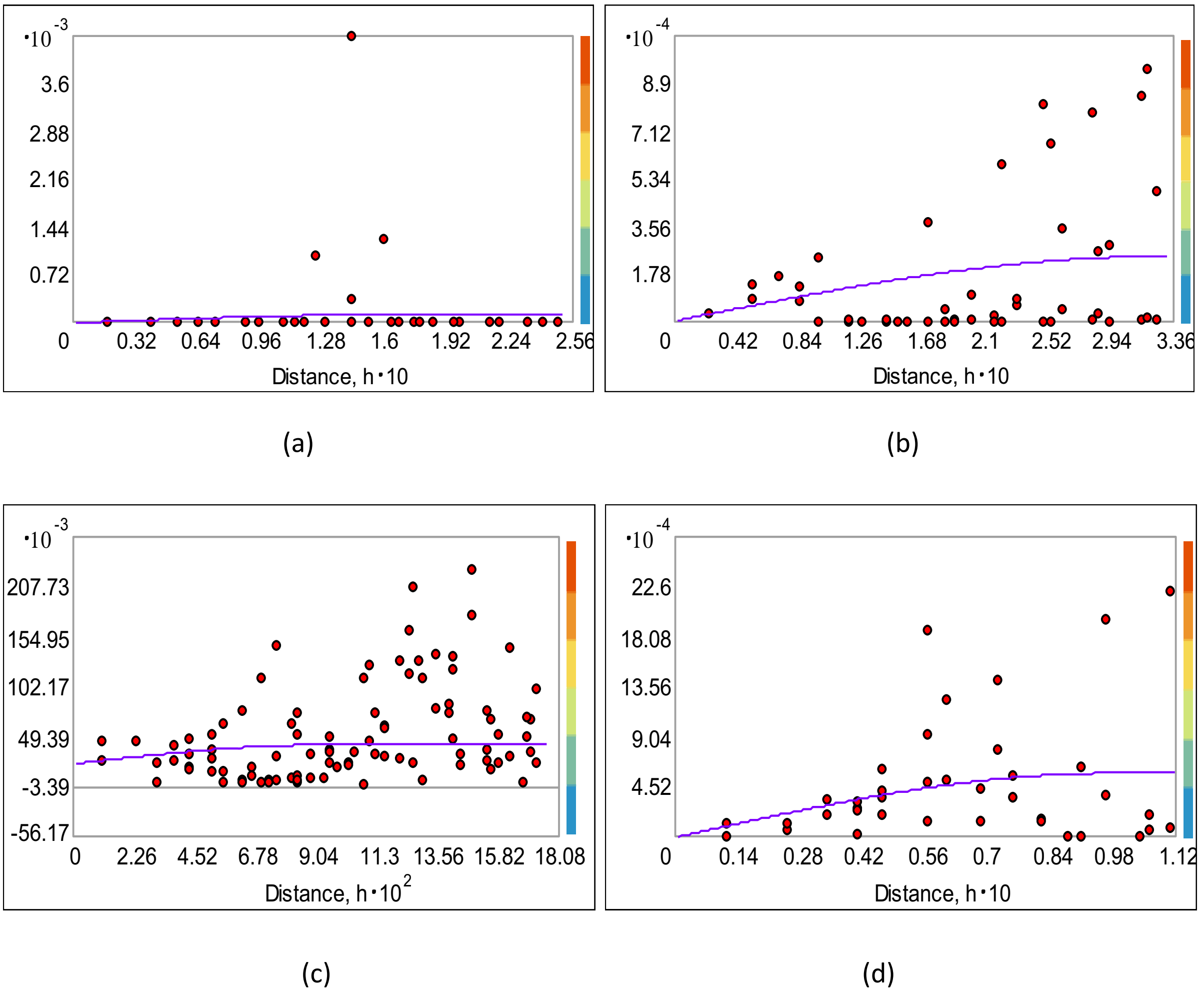


Figure 45: The semivariogram of the desert locust infestations in the early 2004 /2005 season (a), January 2005 (b), February 2005 (c) and March 2005 (d)

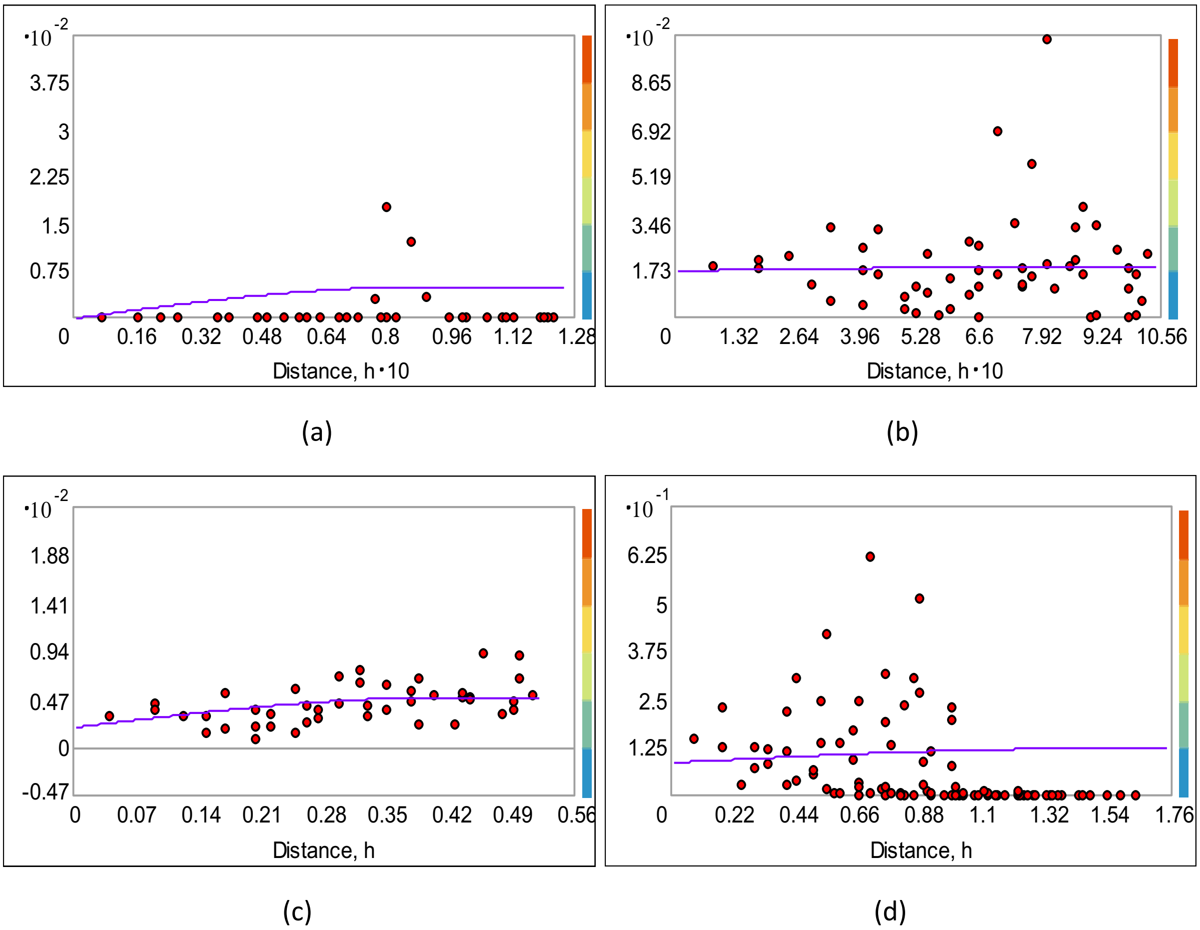


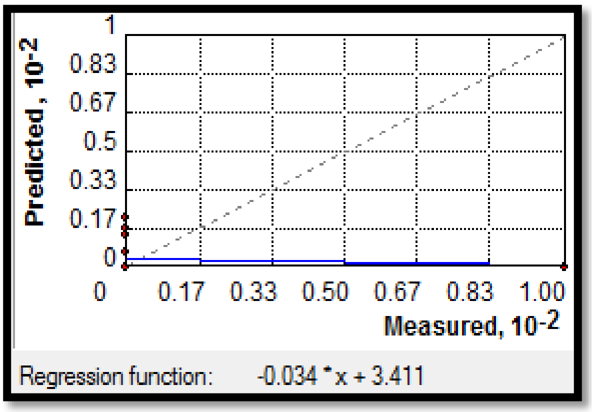
Figure 46: The semivariogram of the desert locust infestations in the early 2006/2007 (a), late 2006/2007 (b), early 2007/2008 (c) and late 2007/2008 (d).

4.3.3. Testing the Kriging Model

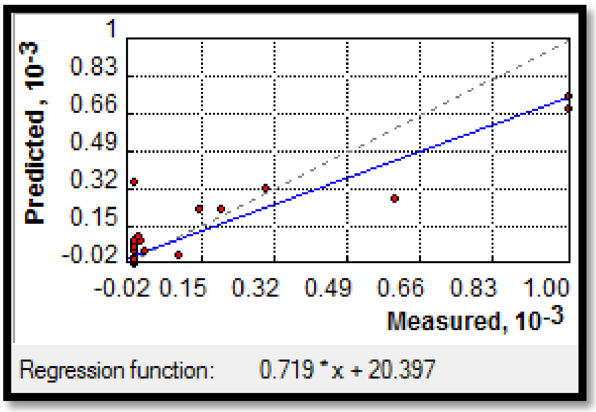
The cross validation indicated both strong and weak correspondences between the predicted and measured infestation sizes. A regression analysis was run between the measured and predicted infestation sizes using SPSS 18 software. It was found that, the regression coefficient differed significantly from 1 (the slope of 45 degree line '1:1 Line') in early 2004/2005 (square r = 0.009, sig. = 0.63) (Figure 47 a), so the kriging model is not accepted. While, the regression coefficient did not differ significantly from 1 in both: January 2005 (square r = 0.78, sig. = 0.00), and March 2005 (square r = 0.54, sig. = 0.00), but the correlation was low in February 2005 (square r = 0.16, sig. = 0.001) (Figure 47 b, c, d).

Therefore, the model performed very well in January 2005, well in March 2005 and fairly well in February 2005.

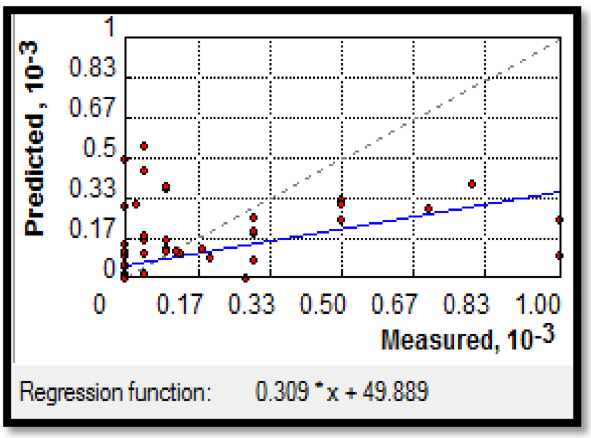
The regression coefficient differed significantly from 1 in both: the early 2006/2007 (square r = 0.002, sig. = 0.8), late 2006/2007 (square r = 0.001, sig. = 0.83), early 2007/2008 (square r = 0.032, sig. = 0.24), and late 2007/2008 (square r = 0.0, sig. = 0.89) (Figure 48 a, b, c, d). Therefore, the model is not accepted in all these cases.



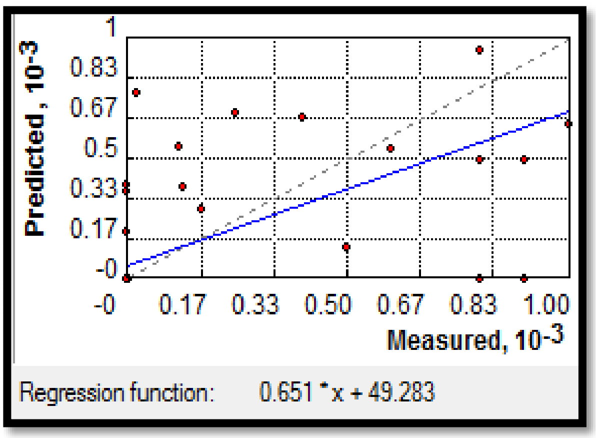
(a)



(b)



(c)



(d)

Figure 47: Scatter plots of predicted against measured infested areas in: early 2004/2005 winter season (a), January 2005 (b), February 2005 (c) and March 2005 (d).

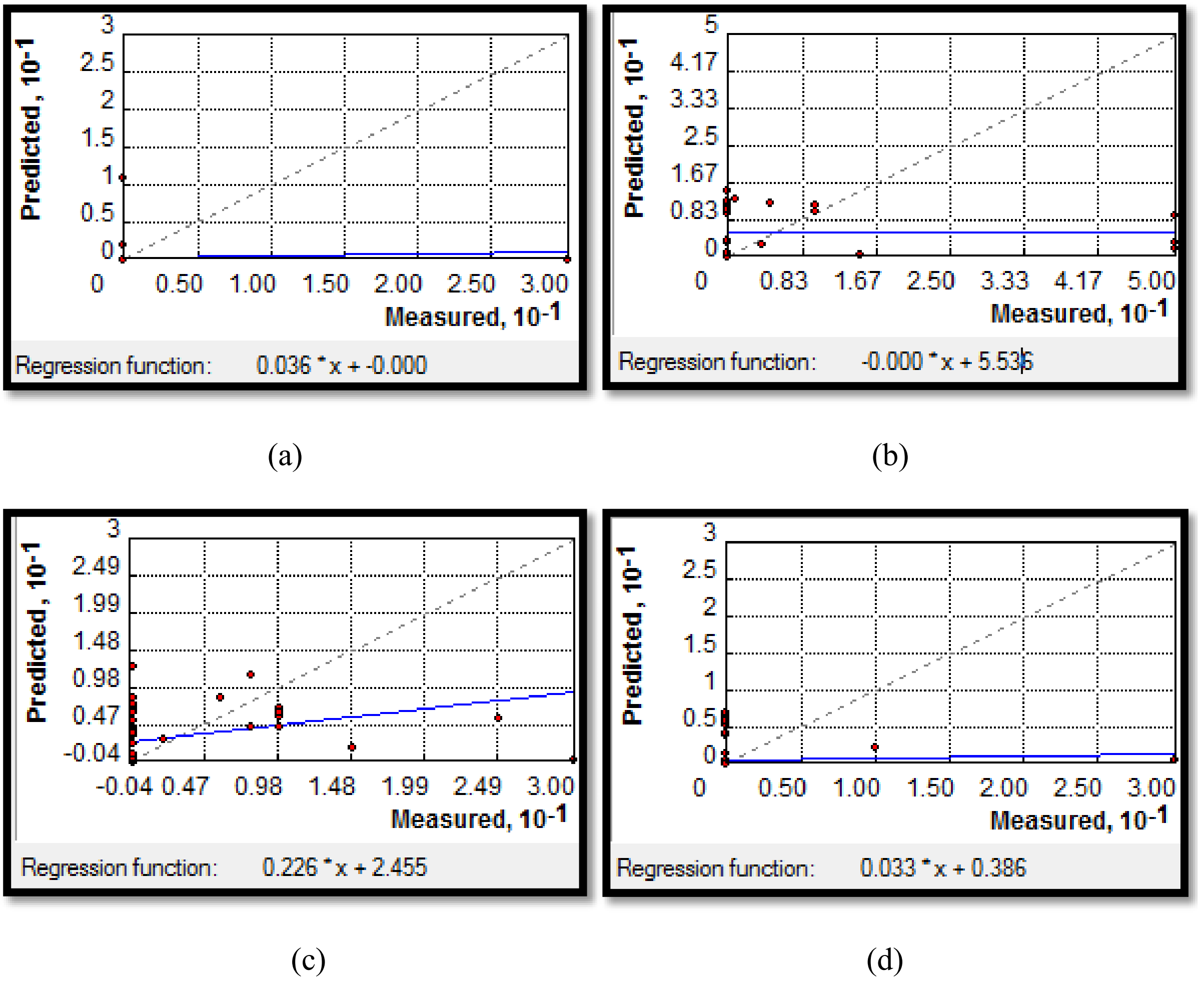


Figure 48: Scatter plots of predicted against measured infested areas in the winter seasons of: early 2006/2007 (a), late 2006 / 2007 (b), early 2007/2008 (c) and late 2007/2008 (d).

- **<u>Discussion for kriging performance</u>**

The above overview for testing kriging proves that, it can be a reasonable model for predicting the size of the desert locust infestation when the data available about infestations are randomly distributed across the area (as in January and March 2005). However, cross validation demonstrated that it was not an efficient method for predicting the infested areas if the data are not accurate and are not randomly distributed across the area, as shown in the other periods.

The limitations of kriging as a method for predicting the size of infestations in the un-surveyed places in some periods may be due to one or more of the following:

- The survey can be repeated in the same site twice in the same month, so that, the infested area at the same location can be measured twice with different values. However, kriging uses only one of those values or their average for the prediction, and this increases the prediction error, as the measured and predicted values will differ greatly.
- In addition, it was observed (by the author on site), that some of the surveyors ignore recording the low numbers of desert locust insects in some sites, and this means that the infested area is 0, while in reality it was higher than 0. Moreover, Ibrahim (2006) found that the estimation of the infested areas by the survey officers differs greatly from the correct estimation. This also causes differences between the measured and predicted values, which in turn weakens the kriging performance in predicting the infested areas.
- Moreover, more survey sites are not randomly distributed across the study area, and the distances between them are not regular, so the data are not suitable for kriging to work well. However, they can be used as a base for investigating the suitability of the proposed prediction method.

- **An alternative survey methodology**

Based on the previous discussion, kriging requires a special survey methodology to perform better. This methodology depends on conducting the surveys stops in regular distances between the survey sites which should be distributed regularly in the surveyed area. The distances should be regular (every 2 kilometers for example), and the survey measurements should be accurate to allow for optimal kriging results.

Chapter Five: General Discussions, Conclusion and Recommendations

5.1. General Discussions

The preventive control strategy was founded in the 1960s; to prevent the occurrence of outbreaks, upsurges and plagues, and control of any significant infestations detected (Magor, Lecoq and Hunter, 2008). To help in achieving the best of this strategy, the extent of the area likely to be infested by the desert locust is required to be demarcated and estimated. This can improve the efficiency of survey results, because most infestations can be found within the mentioned area.

The study provided a method for identifying and estimating the green vegetation area which is likely to be infested utilizing the EVI. This method does not give estimation for the individual infestations, but it gives estimation for the total vegetation areas in which the most infestations can occur. In addition, the idea of identifying and estimating the likely breeding areas depended also on using the EVI, but in this case the likely breeding area is represented by the green vegetation area which found in the sandy soil areas with recent rainfall.

Additionally, the study proposed another method for predicting the infested areas in the non surveyed sites by the locust survey teams. This method depends on using the kriging interpolation, but it was not successful for predicting the infestations in the periods when survey data was not precise. However, it was successful in some other months when the data was suitable.

On another hand, the study investigated the effect of ecological conditions on the desert locust breeding and infestations. In addition it investigated the relationship between green vegetation growth and rainfall occurrence. This was done by using the remote sensing imagery and survey data. In addition, the elevation effect was not very clear, but most infestations occurred mainly at the elevation level of less than 400 meters. Based on these results, the boundary of the likely infested and likely breeding areas could be demarcated and these areas can be estimated to compare them with areas which are monitored by the survey teams, and this can assure if the surveys covered the whole likely infested and breeding areas or not, then they conduct further surveys in the non-surveyed parts.

During the four winter seasons of 2004-2008, 44 % of the survey stops were done within the vegetation extent with less EVI value than 0.05, and 56 % were done within the vegetation extent with EVI value of > 0.05. However, the locust infestations and breeding occurred mainly within the EVI range of > 0.05 to 0.2, so it could be better to carry out the survey in this range.

5.2. Conclusion

The study aimed to improve the efficiency of the desert locust survey operation, and it concluded the following:

1- Rainfall causes outbreaks of desert locusts when it is widespread and heavy, due to its effect on vegetation growth and its provision of suitable soil moisture. However, the seasonal light rainfall does not cause the significant infestations to occur.

2- Infestations occur mainly in the EVI value of > 0.05 to 0.2, and at an elevation level of less than 400 meters.

3- The spatial dependency of desert locusts within the vegetation cover varied greatly across the period of study from less than 0.082 to 0.29 decimal degrees.

4- Kriging interpolation was successful in predicting the infested areas in the unvisited sites by the survey teams in some periods when the data was suitable. However, the model was not successful in other periods due to the inaccuracy of the survey data and their non-normal distribution in the area.

5.3. Recommendations

- It is recommended that the survey operations are conducted within the vegetation extent of elevation at < 400 meters and within the vegetation with EVI value range of > 0.05 to 0.2 after demarcating it. This can save the time and efforts of surveyors and can also lead to decreasing the cost of the operation. In addition, this saving of time and effort can be utilised in conducting further surveys in other suitable locations in order to cover larger areas, and this can increase the chances of finding the most infestations. This recommendation is applied to any areas with similar desert habitat to the study area.
- The application of the kriging technique for predicting the sizes of infestations in the non surveyed sites is also recommended. This depends on using suitable accurate survey data, which is collected specifically for this purpose by well trained surveyors.
- The survey teams should be regularly trained to collect the accurate survey data which can be used for forecasting and also for research purposes in locust management field.
- In addition, further studies are recommended including the following:
  1- Using various vegetation indices with higher resolution than 250 meters, and rainfall images with finer resolution than 25 kilometres, in order to investigate the effect of vegetation and rainfall effect on the desert locust and to estimate the likely breeding and infested areas.
  2- Evaluating the vegetation indices by comparing their value interpretations with the real green vegetation conditions in specific geographic areas, using precise ground

measurements for some periods of time. This is to choose the most suitable vegetation index for the purpose of locust studies.

3- Another study can re-check the kriging interpolation as a method of measuring the infested areas in the non-surveyed sites by the desert locust using accurate data.

4- Additional parameters can be used to study their effect on the desert locust, such as relative humidity, temperature and winds, in addition to the effect of vegetation and rainfall. This is better to be done using survey data of longer periods than 4 years to see how infestation patterns change over longer period.

Has the study achieved its objectives and answered the research questions?

1- The first question and the first objective were related to the effect of ecological conditions on desert locust infestations, and it is clear from the previous findings that rainfall, vegetation and elevation have effects on desert locusts.

2- The second question and second objective were related to estimating the likely infested and breeding areas prior to the occurrence of expected invasion or infestations. This was also possible by using the remote sensing imagery to estimate the vegetation area within which the infestations can occur, and also under the elevation level where these infestations also mainly occurred.

3- The third question and the third objective were related to the possibility of using the survey to predict the sizes of infestation in the unvisited areas by survey teams, and in this sense, kriging did not prove under all cases that it was a suitable method for predicting the size of infested areas. However, it was suitable in some periods which mean that it can be reasonable under the availability of suitable and precise data.

- **Constraints of the study**

Although the study was successful in achieving the aim and objectives and answered the research questions, but it had some limitations which can be summarised as follows:

- The study area was smaller than the optimal sized area for the current condition, as if the study area covered the entire recession area, it could have been able to assure the results in better manner, especially for studying the effect of rainfall on vegetation growth and, identifying and estimating the likely infested and breeding areas. It was chosen with this size, as the most important survey data available only covers this part and as there is not enough data available to cover the entire recession area, which also may require longer period for the study.
- The study investigated the vegetation condition on desert locusts using the EVI, but it could be better if it investigated the effect of vegetation species on desert locusts. However, the details about vegetation species were not available.
- The kriging was used to predict the size of infestations in the un-surveyed places to give an indication about the extent of the infested areas. Nevertheless, it could be better if kriging was used to predict the locust densities, but the data for the later purpose were not available.

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Appendices

Appendix 1: Some Images for the Habitat of the Study Area

Sparse dry vegetation in wadies

Dry desert vegetation

Rainfall in the area

Growing vegetation after rainfall

Solitary adult insect

Copulation of male and female desert locusts

Appendix 2: FAO Survey and Control Form

(The next page) (FAO, no date)

(indicate appropriate information as required)

1	**SURVEY**	**1**	**2**	**3**	**4**	**5**	**6**
1-1	date						
1-2	name						
1-3	latitude (N)						
1-4	longitude (E or W)						
2	**ECOLOGY**						
2-1	area (ha) of survey						
2-2	habitat (wadi, plains, dunes, crops)						
2-3	date of last rain						
2-4	rain amount	L M H	L M H	L M H	L M H	L M H	L M H
2-5	vegetation (dry, greening, green, drying)						
2-6	vegetation	L M D	L M D	L M D	L M D	L M D	L M D
2-7	soil moistur	W D	W D	W D	W D	W D	W D
3	**LOCUSTS**						
3-1	present or a	P A	P A	P A	P A	P A	P A
3-2	area infested (ha)						
4	**HOPPERS**						
4-1	hopper stag	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6
4-2	dominant st	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6	H 1 2 3 4 5 6
4-3	appearance	S T G	S T G	S T G	S T G	S T G	S T G
4-4	behaviour (	I S G	I S G	I S G	I S G	I S G	I S G
4-5	colour (gre	GY GB YB	GY GB YB	GY GB YB	GY GB YB	GY GB YB	GY GB YB
4-6	hopper density (/site, /m2, Low Med High)						
5	**BANDS**						
5-1	band stage	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F
5-2	dominant st	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F	H 1 2 3 4 5 F
5-3	colour (blac	B YB G	B YB G	B YB G	B YB G	B YB G	B YB G
5-4	band density (/m2 or Low Medium High)						
5-5	band sizes (m2 or ha)						
5-6	number of bands						
6	**ADULTS**						
6-1	maturity (in	I M	I M	I M	I M	I M	I M
6-2	dominant m	I M	I M	I M	I M	I M	I M
6-3	appearance	S T G	S T G	S T G	S T G	S T G	S T G
6-4	behaviour (	I S G	I S G	I S G	I S G	I S G	I S G
6-5	breeding (c	C L	C L	C L	C L	C L	C L
6-6	colour (grey	B YW R	B YW R	B YW R	B YW R	B YW R	B YW R
6-7	adult density (/transect (length x width), L M H)						
7	**SWARMS**						
7-1	maturity (in	I M	I M	I M	I M	I M	I M
7-2	dominant m	I M	I M	I M	I M	I M	I M
7-3	breeding (c	C L	C L	C L	C L	C L	C L
7-4	colour (red,	R Y	R Y	R Y	R Y	R Y	R Y
7-5	swarm density (/m2 or Low Medium High)						
7-6	swarm size (km2 or ha)						
7-7	number of swarms						
7-8	flying (from/to, time passing)						
7-9	flying heigh	L M H	L M H	L M H	L M H	L M H	L M H
8	**CONTROL**						
8-1	pesticide name & formulation						
8-2	application rate (l/ha or kg/ha))						
8-3	quantity (l)						
8-4	area treated (ha)						
8-5	ground or a	G A	G A	G A	G A	G A	G A
8-6	estimated % kill						
9	**COMMENTS**						

kc 06.09

Was a GPS used to determine locations? yes Is a brief interpretation or analysis of the results

Country: _ust Officer : __________ date : ________

cleared by : __________ date : ________