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A new GIS-based model for automated extraction of Sand Dune encroachment case study: Dakhla Oases, western desert of Egypt

M. Ghadiry [a,1], A. Shalaby [b,*], B. Koch [c,2]

[a] *Department of Remote Sensing and Landscape Information Systems (FeLis), Faculty of Forest and Environmental Sciences, Freiburg University, Tennenbacherstr. 4, 79106 Freiburg, Germany*
[b] *Land Use Department, National Authority for Remote Sensing and Space Sciences (NARSS), 23 Joseph Tito Street, El-Nozha El-Gedida, P.O. Box 1564 Alf Maskan, Cairo, Egypt*
[c] *Remote Sensing and Landscape Information Systems Department (FeLis), Faculty of Forest and Environmental Sciences, Freiburg University, Tennenbacherstr. 4, 79106 Freiburg, Germany*

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Abstract The movements of the sand dunes are considered as a threat for roads, irrigation networks, water resources, urban areas, agriculture and infrastructures. The main objectives of this study are to develop a new GIS-based model for automated extraction of sand dune encroachment using remote sensing data and to assess the rate of sand dune movement. To monitor and assess the movements of sand dunes in Dakhla oases area, multi-temporal satellite images and a GIS-developed model, using Python script in Arc GIS, were used. The satellite images (SPOT images, 1995 and 2007) were geo-rectified using Erdas Imagine. Image subtraction was performed using spatial analyst in Arc GIS, the result of image subtraction obtains the sand dune movement between the two dates. The raster and vector shape of sand dune migration was automatically extracted using spatial analyst tools. The frontiers of individual dunes were measured at different dates and movement rates were analyzed in GIS. The ModelBuilder in Arc GIS was used in order to create a user

* Corresponding author. Tel.: +202 26251299/1200; fax: +202 26225800/5833.
E-mail addresses: ghadiry@felis.uni-freiburg.de (M. Ghadiry), adelnan@yahoo.com (A. Shalaby), ferninfo@felis.uni-freiburg.de (B. Koch).
[1] Tel.: +49 761 203 3694/8644; fax: +49 761 203 3701.
[2] Tel.: +49 761 203 3694/3695; fax: +49 761 203 3701.

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friendly tool. The custom built model window is easy to handle by any user who wishes to adapt the model in his work. It was found that the rate of sand dune movement ranged between 3 and 9 m per year. The majority of sand dunes have a rate movement between 0 and 6 m and very few dunes had a movement rate between 6 and 9 m. Integrating remote sensing and GIS provided the necessary information for determining the minimum, maximum, mean, rate and area of sand dune migration.

1. Introduction

About one quarter of world's deserts are covered with sand, whereby sand dunes are the most common landforms (McKee, 1979). However, sand dune studies are often met with difficulties arising from the widespread coverage, diversity and complexity of the forming processes. The arid lands are suffering from severe shortage in fertile lands and water resources. However the rapid growth in population has forced the developed countries located in the dry land to develop new desert areas, which could have potential resources. Largely, the encroachment of sand dunes remains one of the key problems that encounter the isolated developed areas within these immense deserts. Therefore, the proper understanding, assessment and modeling the changes of sand dune regimes and their impact on the developed areas are necessary to maintain the fragile resources available and insure their sustainable development.

Research on sand dune has attracted attention since the beginning of the 19th century (Bagnold, 1941). Systematic measurements and relationships between wind velocities and sand flux were founded (Livingstone et al., 2007; Nickling, 1986). Several other studies have focused on the traditional measurement of wind blow and sand flux using different techniques including rotating-cup anemometers, paper flags and sand traps (Knott and Warren, 1981; Livingstone, 1988; Tsoar, 1990). Studying sand dunes in Egypt started by the end of the 19th century with the pioneer works of (Cornich, 1897; Beadnell, 1910; Bagnold, 1941 and Ball, 1939), while the research of (Embabi, 1970 and El-Baz et al., 2000) was the most comprehensive. Literature about dune dynamics, in Egypt, is very limited, where few attempts have been made to investigate dunes' evolution (Mostafa and Embabi, 2002). Since the early thirties of the twentieth century the movement of barchans at the study area (Dakhla) have been studied by different authors and revealed that the migration rates of sand dunes reach between 1 and 16.9 m/year (Embabi, 1986 and Philip et al., 1992).

Remote sensing has been long used for studying sand dune enouncement. Arial photographs were used to study the Al-Huwaimiliyah barchan dune belt in Kuwait, and found that the macro and micro relief of the various geomorphological provinces may influence the rate of sand drift and eventually the magnitude of the sand encroachment potential (Khalaf and AI-Ajmi, 1993). Elhadi et al. (2009) used multi-temporal satellite images (TM and ETM) for monitoring desertification areas. The results showed that the active and semi-fixed sand dunes have increased in the meantime the fixed sand dunes have decreased while several active sand belts have been formed.

Liu et al. (2008) developed a method integrating remote sensing, GIS and field survey to build a sandy desertification dataset for analysis. Tey used Landsat Thematic Mapper (TM) image in 1987, the Enhanced Thematic Mapper Plus (ETM +) image in 2000, and the image with the Charge-Coupled Device Camera (CCD) on the China-Brazil Earth Resources Satellite (CBERS) in 2006. They were able to identify different classes of sand dunes (i.e. active, fixed, semi-fixed dunes) and inter-dune grassland. Landsat TM images, field data, and laboratory reflectance spectra were examined for the Kelsodunes, Mojave Desert, California to assess the use of visible and near-infrared (VNIR) remote sensing data to discriminate eolian sand populations on the basis of spectral brightness, it was found that average TM spectral DN values for active units are higher (brighter) than average spectra of inactive units, (Paisley et al., 1991).

Zhibao et al. (2000) used the means of a topographical survey in late 1991, 1992 and 1993 to monitor the sand dune movement in the Taklimakan Desert, China in a sample plot along the desert crossing highway. The mean advance rate of the dunes was 7.29 and 5.56 m yearly in 1992 and 1993, respectively. They concluded that the relationships between advance rate and the morphometric parameters of the dunes are variable for the immature dunes. The small scale and immaturity of the dunes, insufficient sand supply, and complex wind modes are responsible for the complex dune parameter relationship, involving frequent changes of dune morphology, as well as changes of dune advance rate. Necsoiu et al. (2009) developed a novel method to quantify subtle rates of landscape evolution using two satellite imaging systems with different viewing angles and spectral sensitivities. They selected the slowly migrating, high latitude, subarctic Great Kobuk Sand Dunes (GKSD), Kobuk Valley National Park, Alaska (USA). They used ASTER Visible Near Infrared (VNIR) and SPOT Panchromatic images with a 5-year temporal separation to measure the horizontal velocity of the GKSD. The results show that the most likely migration rate for the GKSD ranges from 0.5 to 1.5 m/year, with peak velocities up to 3.8 m/year, and uncertainty of approximately 0.16 m/year. (Mohamed, 2010) used two satellite images to study the sand dune drift in the western desert of Egypt. He found that a maximum advance rate of about 9 m/year at the southern part of the desert.

The objectives of this study are to develop a new GIS-based model for automated extraction of sand dune encroachment using remote sensing data and to assess the rate of sand dune movement.

2. Study area

Dakhla Oases is located in the western desert of Egypt, about 750 km southwest of Cairo, between latitudes 25° 31′ and 25° 41′ 30″ N, and 28° 46′ 30″ and 29° 2′ E (Fig. 1). The study region covers an area of approximately 500 km^2. The floor of Dakhla depression is bounded from the north and north east

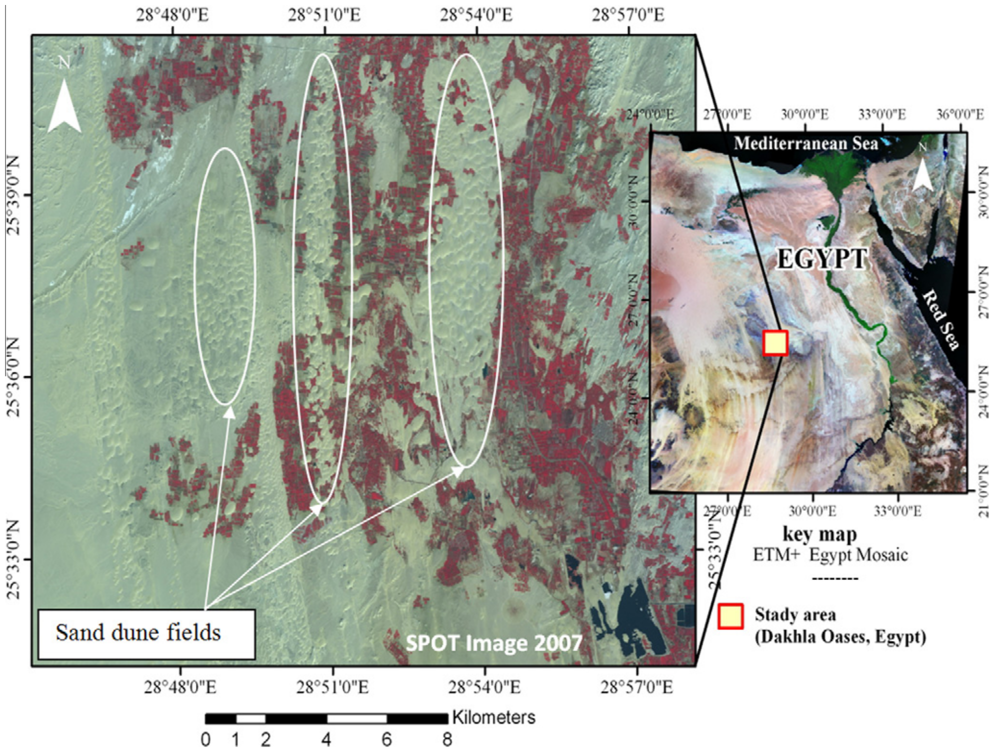

Figure 1 Location of the study area (Dakhla oases, western desert of Egypt).

by steep scarps of the Eocene Limestone plateau, but gradually rises to the south where it merges with the plain of Upper Cretaceous Nubian sandstone. It is estimated that 30,000 acres of land are being cultivated within the Dakhla Oases. The recent estimate of population shows that 70,000 residents are settled in the rural areas of the depression, most of them are farmers who are struggling against the threats of mobile sand dunes on their fields. The main prevailing wind is North–Northwest; a bi-directional wind system that probably caused the sinuosity of the northern dunes (GAD, 1988). In the southern part of the area, the diversity of wind pattern is reflected by the existence of diverse sand dunes (i.e. Barchan, inter-dune areas). Some of the inter-dune areas have been recently cultivated, which give the dunes the appearance of being stabilized. However, it is recorded that the dunes are still advancing and threatening the nearby farmlands and urban areas in Dakhla Oases.

3. Methodology

The methodology flow chart (Fig. 2) summarizes all processing and analysis that have been done to fulfill the objectives of this research.

3.1. Data set

In this study, two SPOT images were used to calculate the migration rates of sand dunes around the major sensitive locations in the study area. Multi-temporal SPOT images (1995, 10 m & 2007, 2.5 m) were acquired form OASIS Programme CNES, France (http://medias.obs-mip.fr/oasis/). The images were geo-rectified using ground control points. This was performed with RMS registration errors ranging from 0.2 to 0.3 pixels for both images. SPOT 1995 were resized from 10 to 2.5 m spatial resolution, in order to be equivalent with the same pixel size of the Spot 2007 2.5 m. All images were acquired in the winter season of the years 1995 and 2007.

3.2. Data preparation and pre-processing

For the SPOT images, the pre-processing step includes the various procedures that are required to remove radiometric and geometric errors from the satellite images (Schiek, 2004). In this research the following pre-processing were carried out:

3.2.1. Geometric correction

Accurate per-pixel registration of multi-temporal remote sensing data is essential for change detection (image subtraction) since the potential exists for registration errors to be interpreted as land-cover and land-use change, leading to an overestimation of actual change (Stow, 1999). Change detection analysis is performed on a pixel-by-pixel basis; therefore any misregistration greater than one pixel will provide an anomalous result of that pixel. To overcome this problem, the RMSE between any two dates should not exceed 0.5 pixels (Lunetta and Elvidge, 1998). In this study, Geometric correction was carried out for the SPOT image of 2007 using 25 ground control points (GCP's) obtained from a digital topographic map at a scale of 1:10,000. Using the image to image technique, the SPOT image of 2007 was used to perform the geometric correction of the other SPOT image dated 1995. The RMSE between the two images was less than 0.5 pixels.

3.2.2. Image enhancement

The goal of image enhancement is to improve the visual interpretability of an image by increasing the apparent distinction

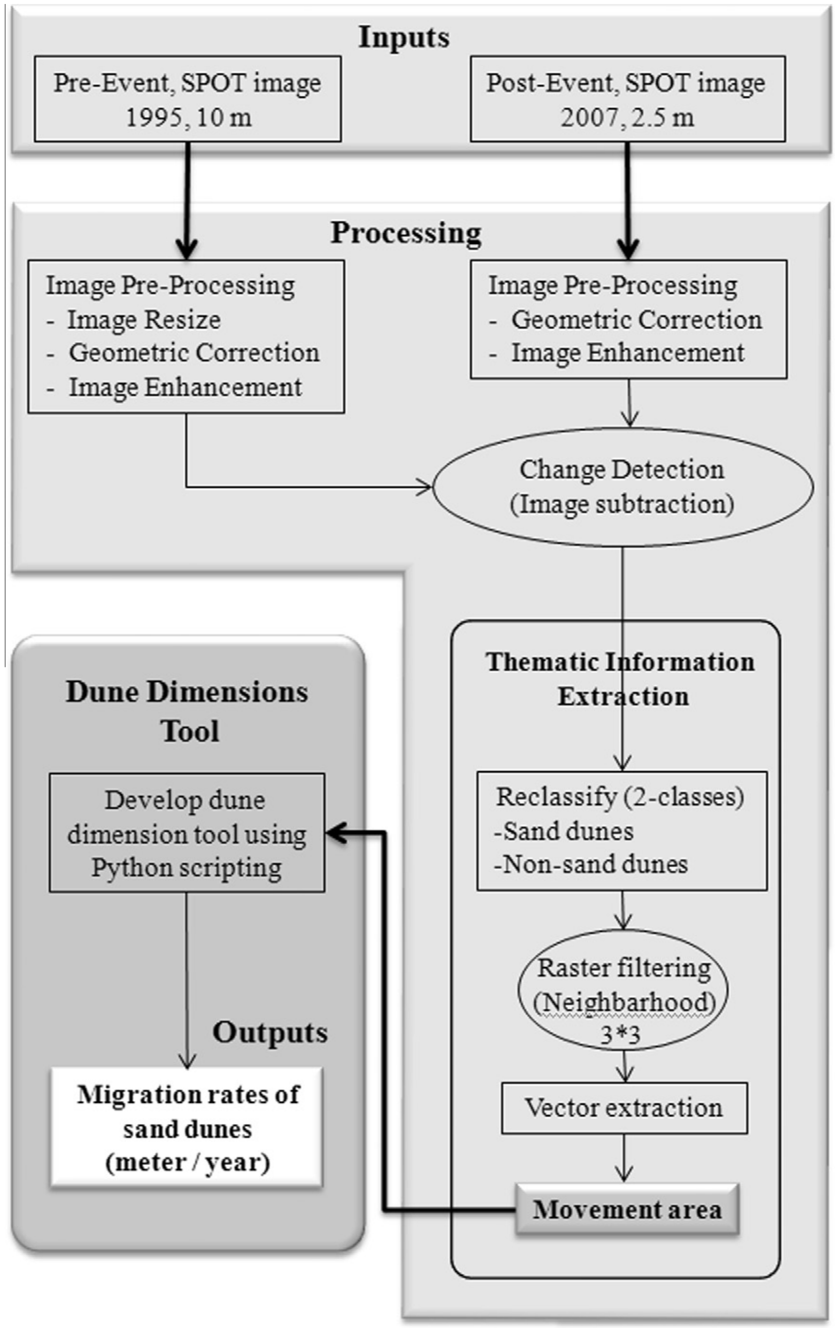

Figure 2 Flowchart of the methodology.

between the features. The Percentage Linear Contrast Stretch technique was used to enhance the two SPOT images (1995 and 2007). The percentage linear contrast stretch is similar to the minimum–maximum linear contrast stretch except this method uses specified minimum and maximum values that lie in a certain percentage of pixels from the mean of the histogram. A standard deviation from the mean is often used to push the tails of the histogram beyond the original minimum and maximum values. (Salem et al., 2010). Focal statistic enhancement technique was also applied on both satellite images in order to increase the visual interpretability of the images and to facilitate the delineation of sand dunes.

3.2.3. Image sub-setting

The clip function in Arc GIS9.3 under data management was used for sub-setting. A sub-set of the two images was cut to cover the study area. Since the two images are from two different sensors and they do not cover exactly the same area, a subset has to be made in order to carry out the change detection. Arc GIS software was used to clip both images via clip function.

3.2.4. Pixel resizing

The pixel size of SPOT-5 image of 2007 has a pixel size of 2.5 m while the pixel size of 1995 SPOT-3 image is 10 m. When elaborating change detection process, the pixel size of different images must be exactly the same, therefore, neighborhood statistic function was used to resize the pixel size of 1995 SPOT image from 10 to 2.5 m.

3.3. Sand dune movement extraction using image subtraction technique

This step aims to detect changes within dune field spatial extent, over the SPOT images (1995 and 2007). Image subtraction technique computes the differences between two images with two different acquisition dates and highlight changes that happened over time (Arc GIS help, 2010). Image subtraction function in Arc GIS 9.3 was used to calculate changes between SPOT image acquired in 1995 and SPOT image acquired in 2007 via this operation the value of the second input raster was subtracted from the value of the first input raster on a cell by cell basis within the analysis window. This step resulted in defining areas where dune migration and advancement took place. The following processes were carried out in order to enhance the result of the subtraction technique.

3.3.1. Enhancement of the subtraction result

The resultant image of the subtraction process had noises. In order to remove these noises a number of enhancement technique were used. These enhancement techniques includes.

3.3.2. Focal statistics

The focal statistic function 3*3 under spatial analyst in Arc GIS was used to improve the result of image subtraction. The focal statistic tool performs a neighborhood operation that computes an output raster where the value for each output cell is a function of the values of all the input cells that are in a specified neighborhood around that location.

3.3.3. Slicing

Slicing reclassifies the range of values of the input cells into zones of equal interval, equal area, or by natural breaks. In this study the result image of the focal statistic was classified into equal intervals to two classes. The first class represents sand dune movement and the second class represents sand sheets.

3.3.4. Reclassify

The reclassify tool under spatial analyst in Arc GIS was used to separate the movement of sand dune from sand sheets, the sand dune movement was given the value 1 and the sand sheet was given the value NoData.

3.3.5. Raster to polygon conversion

When you convert a raster dataset containing area features, each group of contiguous cells with the same values converts into a polygon. Arcs are created from cell borders in the raster. NoData cells in the input raster do not become polygons in the output. The raster sand dune movement map was converted to vector format to calculate the movement rate of sand dunes.

3.3.6. Smoothing

This operation is used to smooth sharp angles in polygon outlines to improve the esthetic or cartographic quality. A tolerance of 10 m was used to remove the noises.

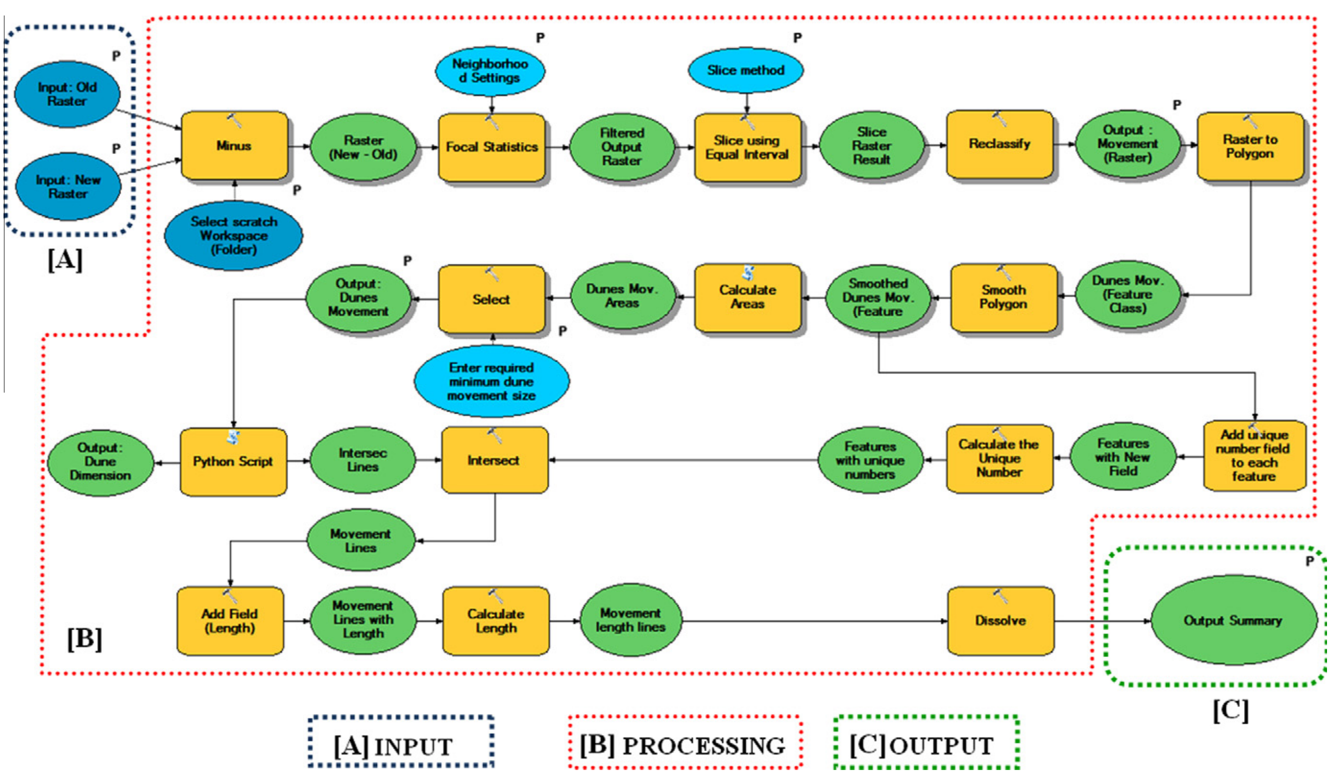

Figure 3 The workflow of used geo-processing in Model Builder.

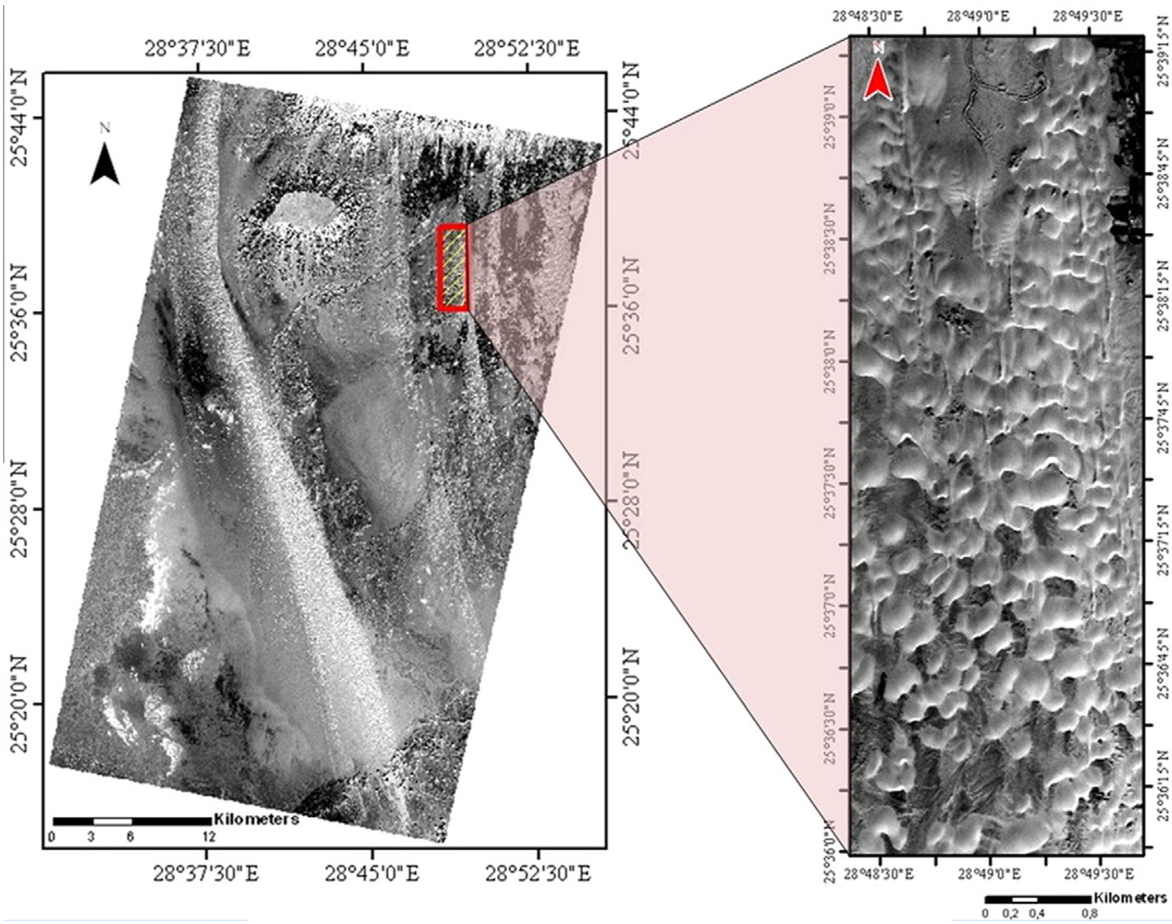

Figure 4 A sample area that represents the most active sand dunes.

3.4. Creation of Dune Dimension Tool (DLL) using Python programming language

Python is an interpreted language that can be run at the command line in a Python command window or using a Python editor/debugger. DDL was developed in a combined environment of GIS and dynamic object-oriented programing. Vector data that represent the sand dune movement were processed in Arc GIS 9.3 and exported as an ASCII raster grid as an input to Python. Using Python script a minimum boundary rectangle around each sand dune movement polygon was created. A number of transect lines were created inside the rectangle. The main reason behind forming transect lines in each feature is to measure the minimum and maximum movements of each dune.

3.5. ModelBuilder tool development

The ModelBuilder was created in ArcToolbox and found useful in this work as it enable the developer to adapt the existing tools according to the demand and situation. The geo-processing tasks were carried out in a step-wise and integrated manner using a customized tool under ModelBuilder. The ModelBuilder uses each function to create designated output. The output of each function is the input for another function. (Fig. 3) shows the created ModelBuilder.

4. Results

4.1. Sand dune movement extraction using image subtraction technique

A sample area (Fig. 4) that represents the most active sand dunes is studied in detail. This sample area covers an area of 1355.6 hectares and has 122 sand dunes. Image subtraction technique was applied and Fig. 5 shows the two SPOT images of 1995 and 2007 covering the same sample area and the result of subtraction to the right side of the figure. Focal statistics was applied to improve the result of image subtraction. The focal statistic function 3*3 under spatial analyst in Arc GIS has been used. The focal statistic tool performs a neighborhood operation that computes an output raster where the value for each output cell is a function of the values of all the input cells that are in a specified neighborhood around that location.

4.1.1. Enhancement of the result of subtraction

The resultant image of the subtraction process had noises. In order to remove these noises a number of enhancement techniques were used. These techniques included.

4.1.1.1. Slicing. The result image of the focal statistics was classified in equal intervals into two classes. The first class represents sand dune movement and the second class represents

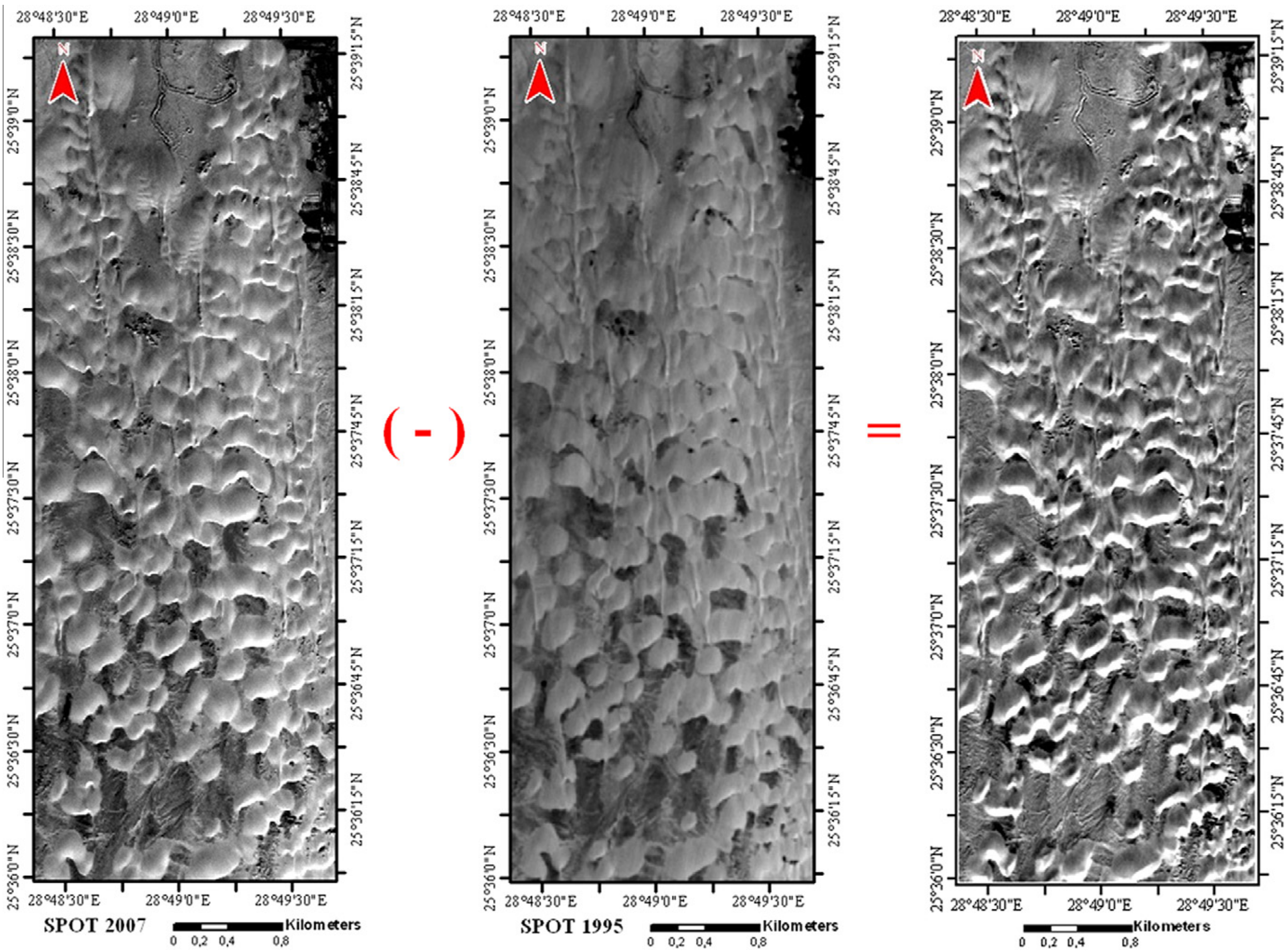

Figure 5 Image subtraction for two SPOT images of 2007 and 1995.

sand sheets as shown in Fig. 5. The resulting image from the subtraction process was reclassified into two classes using the reclassify tool in Ar cGIS, where the first class represents sand dunes and the other class represents non-sand dune land cover types (Fig. 6).

4.1.1.2. Raster to polygon conversion. When you convert a raster dataset containing area features, each group of contiguous cells with the same values converts into a polygon. The raster sand dune movement map was converted into vector. Smoothing function was used to smooth the sharp angles in the polygon outlines in order to improve the esthetic or cartographic quality. A tolerance of 10 m was used to remove the noises as shown in (Fig. 7).

4.2. Dune dimension tool development using Python programming language

Dune Dimension Tool (DDL) was created to measure the movement of individual sand dunes. This Python script based tool was developed to carry out automated measurement of sand dune movement. The tool creates minimum boundary rectangle around each polygon (sand dune movement) and transect lines inside the rectangle are created (Fig. 8). The transect lines are found necessary for measuring minimum, maximum and mean of each sand dune movement. To accommodate the various kinds of movement shapes, it was concluded that seven transect lines are optimal.

4.3. ModelBuilder tools for dune movement detection

Geo-processing tasks can be time intensive because they are often performed on many different datasets. Therefore, scripting is used to automate geo-processing tasks. Scripting allows the execution of simple processes that employ a single tool for complex processes. In addition, scripts are recyclable, because they are data nonspecific.

The ModelBuilder was used in this research to create a user friendly tool for calculating sand dune movement using existing tools within ArcToolbox and modified with custom model sub-components and scripts. These tools are easy to run within a custom dialog and the results are easily repeatable. **(**Fig. 9) shows the end user tool produced from the ModelBuilder. The ModelBuilder tool uses the input two raster images and finally gives the length of the movement of the sand dunes discarding the intermediate and non-desirable outputs.

The custom built model window is easy to handle by any user who wishes to adapt the model in his work. The ModelBuilder was compiled and tested in Window XP as well as Window 7 Operating System S with 32-bit and 64-bit processors. The process run time for the entire process, for 1355.6 hectare area containing 122 sand dunes using Windows 7 OS

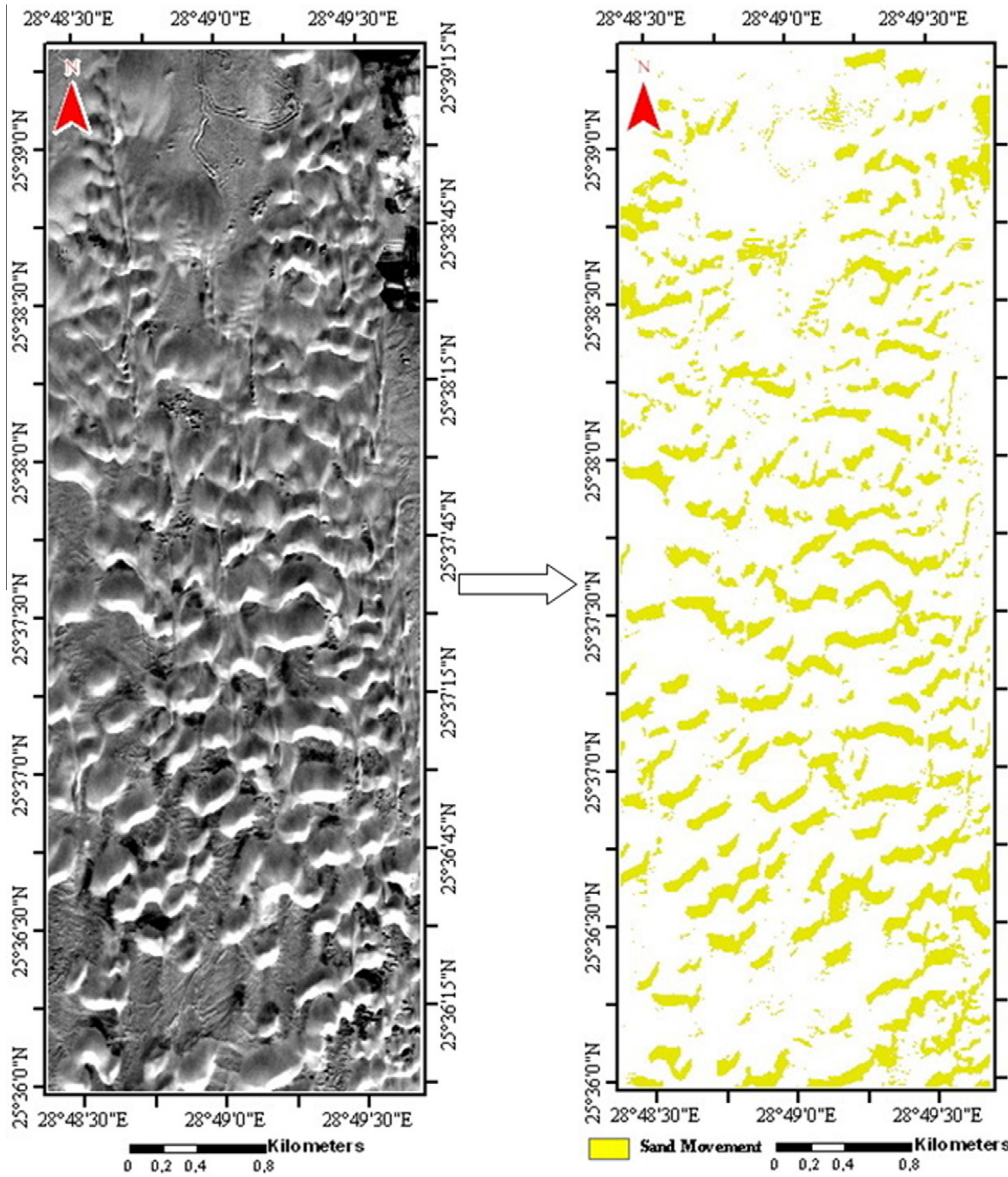

Figure 6 Sand dune movement map before and after slice and reclassify.

with 4 GB RAM and 2.2 GHz Intel Core Duo processor is 34 s (Fig. 10).

Another advantage of the ModelBuilder is that the user can export the Arc GIS models directly to the Python scripts. And the user then can make necessary changes in the script itself, if any, and run the script directly from the command line options.

4.4. Minimum movement of sand dunes

The minimum movement of all sand dunes in the study area was estimated using automated measurement. (Table 1) summarizes the minimum movement of sand dunes, where very few dunes (5 dunes) have a minimum movement between 0 and 10 m during the study period from 1995 to 2007. The majority of sand dunes have a minimum movement between 10 and 50 m. Only 8 dunes have the minimum movement of more than 50 m.

4.5. Maximum movement of sand dunes

The maximum movement of all sand dunes, in the study area, was measured using automated measurement method. Table 2 summarizes the maximum movement of sand dunes where,

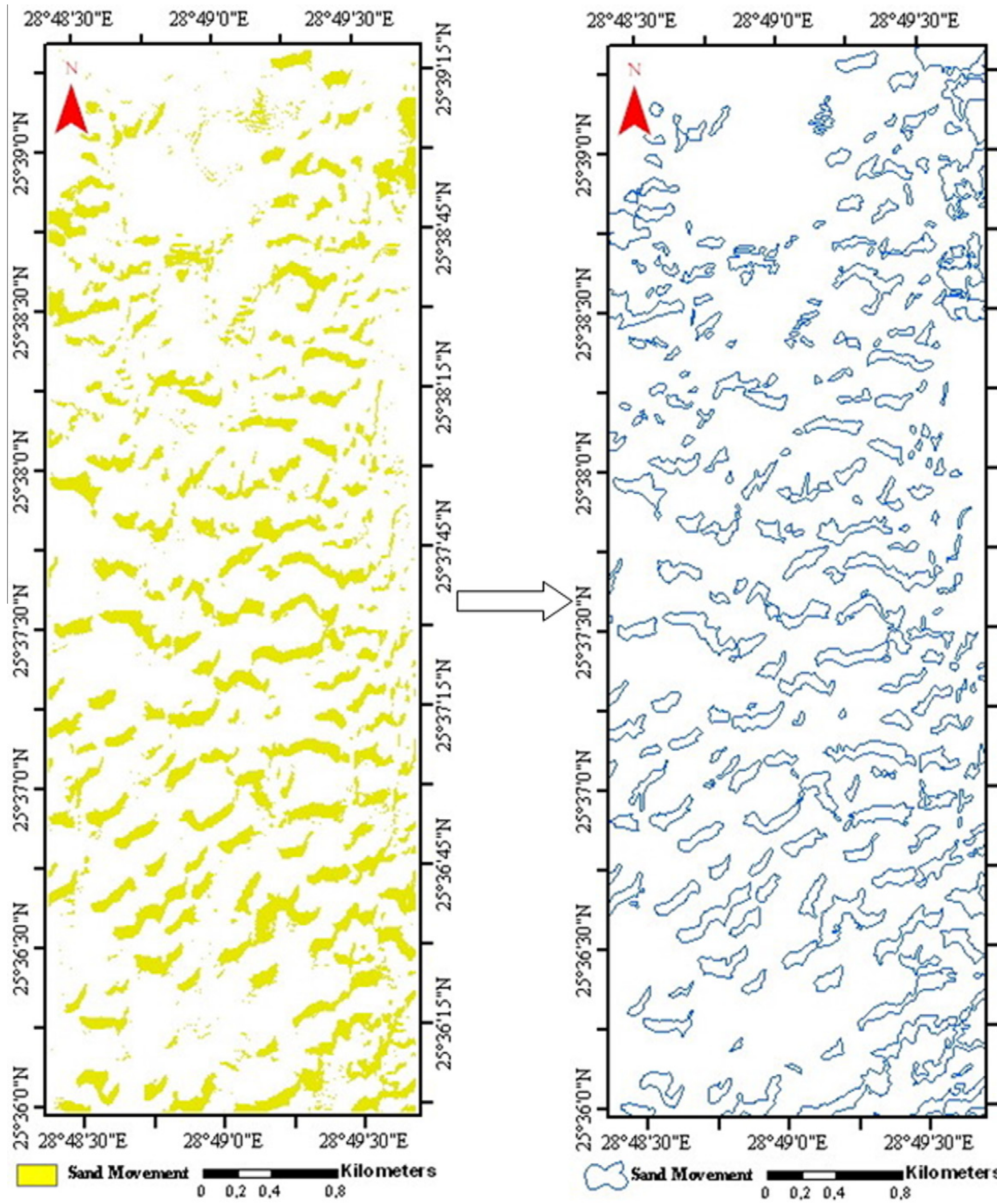

Figure 7 Raster to polygon conversion of sand dune movement map.

only 2 dunes have a maximum movement between 0 and 30 m. The majority of sand dunes have a maximum movement between 30 and 120 m. Only 10 dunes have the maximum movement of more than 120 m.

4.6. Mean movement of sand dunes

The mean movement of all sand dunes in the study area was measured using automated measurement method. Table 3 summarizes the mean movement of sand dunes where, no dune has a mean movement between 0 and 20 m. The majority of sand dunes have a mean movement between 20 and 80 m. Only 6 dunes have the mean movement of more than 80 m.

4.7. Rate of mean sand dune movement

The rate of movement of all sand dunes in the study area was measured using automated measurement method. (Table 4) summarizes the rate movement of sand dunes where, only 5 dunes have an annual rate movement between 6 and 9 m (from 1995 to 2007). The other 117 sand dunes have an annual rate movement between 0 and 6 m.

4.8. Movement area of sand dunes

The movement area of all sand dunes in the study area was measured using automated measurement method. (Table 5)

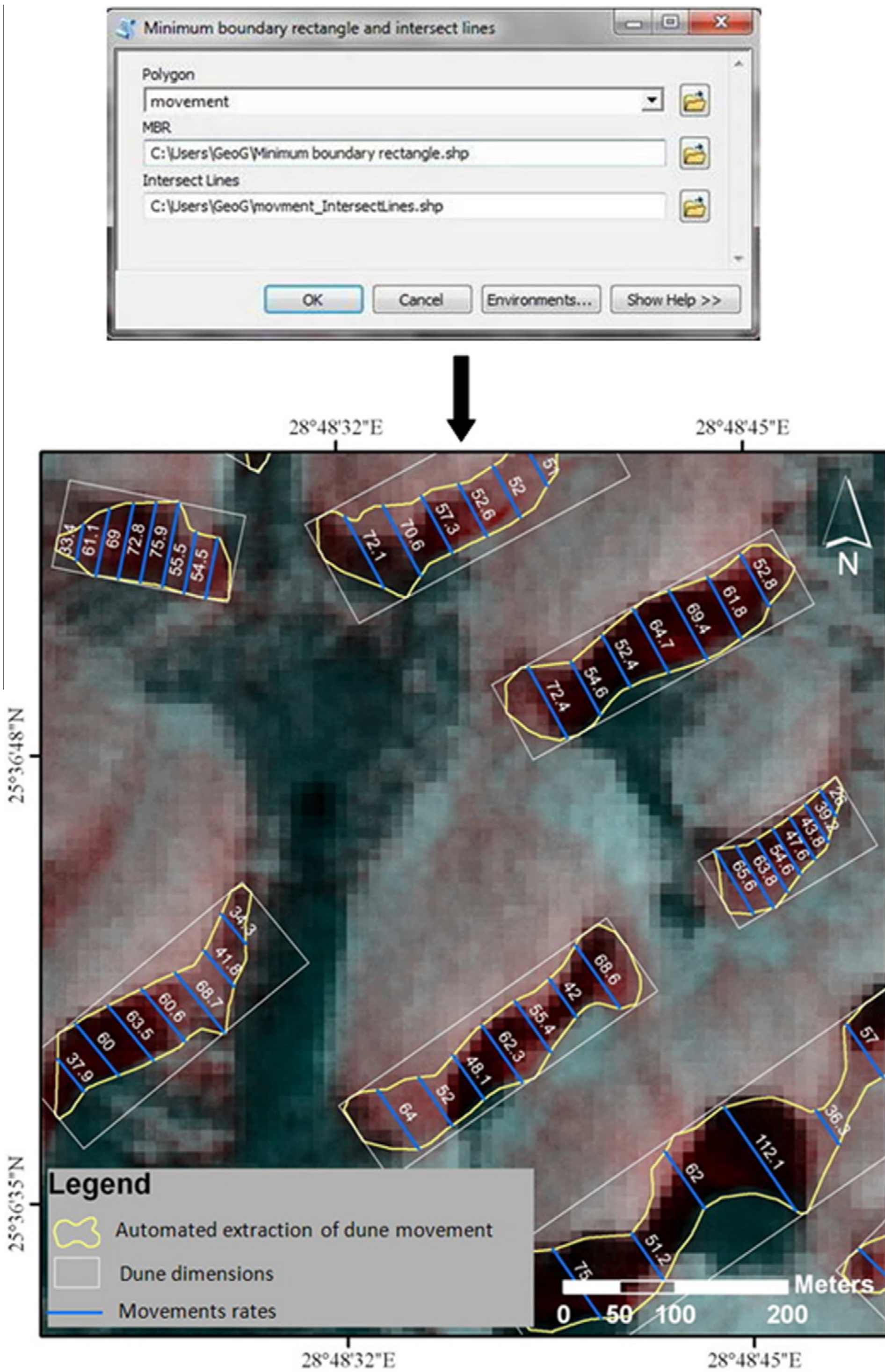

Figure 8 Window tool shows the creation of minimum boundary rectangle and transect lines with length in meter.

summarizes the movement area of all sand dunes where, only 2 dunes have a movement area between 4 and 7 hectares (from 1995 to 2007). The majority of sand dunes have a movement area between 0 and 2 hectares, 92 dunes or 75.4%. Only 27 dunes have a movement area between 2 and 4 hectares.

4.8.1. Conclusions and recommendations

The objectives of this study were to develop a new GIS-based model for automated extraction of sand dune encroachment using remote sensing data and to assess the rate of sand dune movement. Different Arc GIS functions were used in this study to detect the dune movement. These functions include image subtraction, focal statistic slice, reclassify, raster to polygon, smooth polygon, intersect, dissolve and calculate area. The ModelBuilder was used to simplify the process of using all the previous functions. The ModelBuilder was integrated with Python script in order to create a dune dimension tool. This tool is a simple window that contains fields for the input (mul-

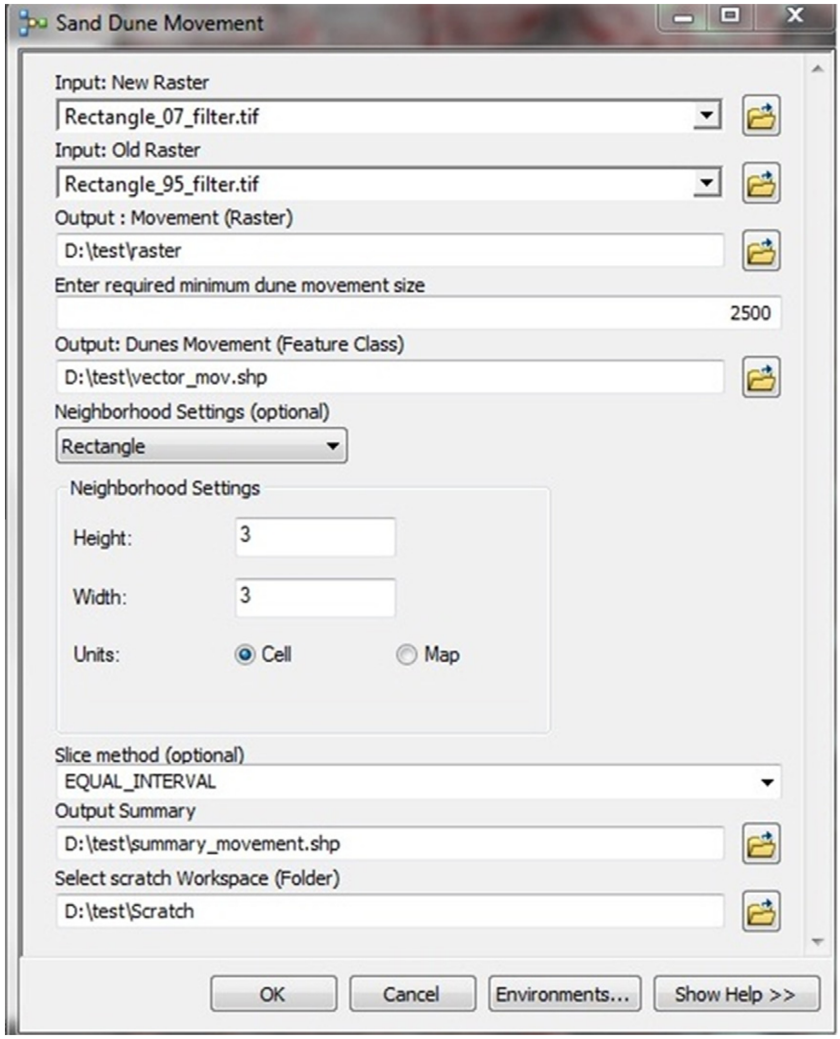

Figure 9 End user window perused from the Model Builder.

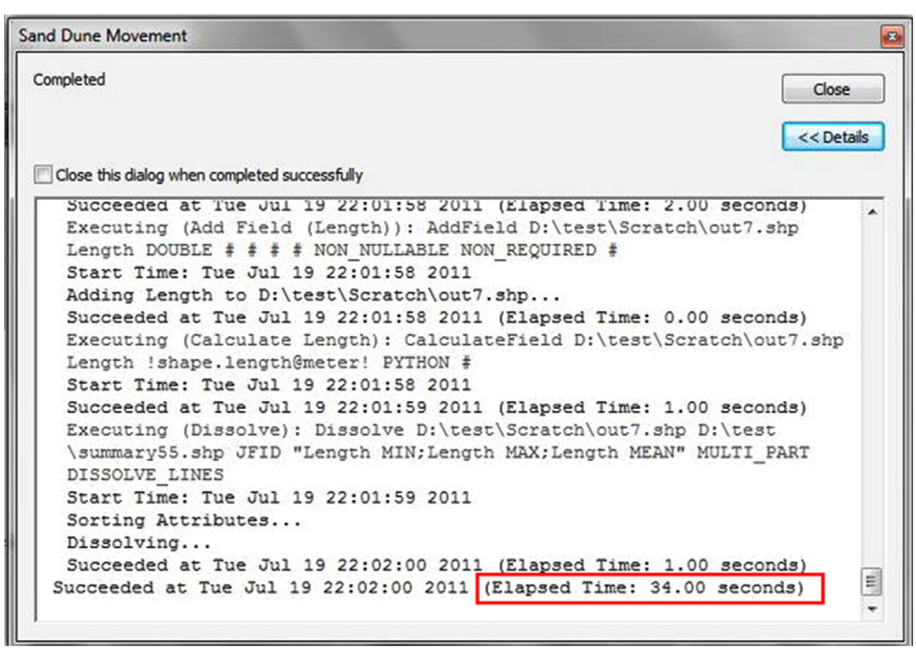

Figure 10 Template set used for the sample application shows the elapsed time for the whole process.

Table 1 Minimum movement of sand dunes.

Number of dunes	Minimum movement(m)
5	0–10
24	10–20
35	20–30
34	30–40
16	40–50
6	50–60
2	60–70
0	70–80

Table 2 Maximum movement of sand dunes.

Number of dunes	Maximum Movement(m)
2	0–30
32	30–60
57	60–90
21	90–120
8	120–150
2	150–180
0	180–210

Table 3 Mean movement of sand dunes.

Number of dunes	Mean Movement(m)
0	0–20
28	20–40
47	40–60
41	60–80
5	80–100
1	100–110

Table 4 Rate of sand dune movement.

Number of dunes	Mean Movement per year(m)
40	0–3
77	3–6
5	6–9

Table 5 Movement area of sand dunes.

Number of dunes	Movement area (hectares)
51	0–1
42	1–2
16	2–3
11	3–4
1	4–5
0	5–6
1	6–7

ti-temporal satellite images) and outputs (minimum, maximum, mean, rate and movement areas).

The ModelBuilder tool uses the input two raster images and finally gives the length of the movement of the sand dunes discarding the intermediate and non-desirable outputs. The custom built model window is easy to handle by any user who wishes to adapt the model in his work. The process run time, for 1355.6 hectare area containing 122 sand dunes using Windows 7 OS with 4 GB RAM and 2.2 GHz Intel Core Duo processor is 34 s.

The rate of movement of all sand dunes in the study area was measured using our automated measurement tool. The rate of sand dune movement ranged between 3 and 9 m per year. The majority of sand dunes have a rate movement between 0 and 6 m and very few dunes had a movement rate between 6 and 9 m.

Integrating remote sensing and GIS provided the necessary information for determining the minimum, maximum, mean, rate and area of sand dune migration. The automated measurement method has the advantageous of being robust, easy to carry out and cheaper than the manual extraction through on screen digitizing.

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