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Research Paper

Geospatial techniques for environmental modeling of mosquito breeding habitats at Suez Canal Zone, Egypt

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ABSTRACT

Egypt is currently witnessing a number of mega projects, along the axis of Suez Canal, which consequently have a great effect on environment and its biological components including mosquito vectors of diseases. This study is an attempt to explore the use and efficiency of integrated remote sensing-GIS techniques and field surveys for detection of mosquito breeding habitats at Suez Canal Zone. Remote sensing and field surveys provided the necessary verified ground truth information to the present study. A corrected Landsat8 image, acquired in Jan. 2015, was utilized to produce NDVI, NDMI and LST to identify environmental variables associated with mosquitoes breeding habitats. Concurrently, a GIS model was developed to predict probable mosquito habitats and areas under environmental risk of diseases transmission. Results revealed that *Culex pipiens* and *Ochlerotatus detritus* are the most abundant species in Suez Canal Zone recording total number of 362 larvae (51.86%) and 244 larvae (34.96%), respectively. The model predicted that Ismailia is the most subjected Suez Canal Governorate to mosquito borne diseases. It recorded the maximum levels of high risk, risk and vulnerable areas to mosquito proliferation; 6.06 km^2 (64.26%), 954.65 km^2 (54.58%) and 152.87 km^2 (80.09%), respectively. The developed prediction model achieved an accuracy of 80.95% and increased to 100% at sites where predicted larval habitats were ascertained by *in-situ* checks.

1. Introduction

Egypt is currently witnessing a number of mega projects, along the axis of Suez Canal, that aim to expand agricultural lands and logistics services in addition to ease population pressures on contracted Delta. These projects induce changes in land use/land cover which consequently have a great effect on environment and its biological components including mosquito vector of diseases (Abdel-Hamid et al., 2011). Such environmental disturbances may provide suitable habitats for mosquito vectors allowing their wider distribution into and around the project areas. All of these factors may cause health risks from emerging or re-emerging vector-borne diseases that would have impacts on the integrity of development projects aiming for the prosperity of Egyptians (Hassan et al., 1999, 2004; Hassan, 2001; Hassan and Onsi, 2004; Abdel-Hamid et al., 2011). The Suez Canal Zone is characterized by the distinguished energetic and environmental nature; therefore various mosquito species are spread in and around the area. Urban extension, dissimilar urban areas, existence of rural and desert areas consequently lead to the diversity of mosquito habitats (Martens and Hall, 2000).

Mosquitoes have a greater importance in terms of major public health problems. Approximately one million people died because of mosquito-borne diseases and about 247 million people become ill in tropical and subtropical areas of the world in 2006, as reported by the World Health Organization (WHO, 2008). The number of deaths was estimated to be decreased in 2009 to 781,000 (WHO, 2010). Different mosquito species belonging to genera *Culex*, *Aedes* and *Anopheles* serves as significant vectors of several serious diseases (Weaver and Reisen, 2010; Kilpatrick, 2011). This is arisen as a result of their abundance, ability for mosquitoes to carry disease-causing pathogens, recurrent infection and diversity (Njabo et al., 2013). Moreover, mosquito bites may cause a significant nuisance for mammals and humans which may have adverse economic consequences (Connelly and Carlson, 2009).

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Mosquitoes were irregularly surveyed starting from 1903 in Suez Canal Zone and continued till 1981 (Kenawy, 1988). Such surveys were followed by different investigators (i.e. El-Said and Kenawy, 1983; Harbach et al., 1988; Cope et al., 1995; Abdel-Hamid et al., 2011 and Abdel-Hamid et al., 2013; Ammar et al., 2012). According to these surveys, twenty-nine mosquito species belong to five genera (i.e. *Culex, Anopheles, Culiseta, Aedes* and *Uranotaenia*) have been encountered in the different parts of Egypt (Tawfick, 1990; Morsy et al., 2003). Twelve of these species were reported in Ismailia Governorate/Canal Zone (El-Said and kenawy, 1983; Harbach et al., 1988; kenawy and El-Said, 1990; Morsy et al., 1990; Bahgat et al., 2004).

Suez Canal Zone has an old history of vector borne diseases where about one third of the Suez Canal population was infected by malaria (Halawani and Shawarby, 1957). In 1936, very high malaria indices were detected in Ismailia governorate (Barber and Rice, 1937). Between 1982 and 1991, malaria was reported in 7 governorates including Port Said and Suez (Hassan et al., 2003). By the end of 1998 till now, no local cases were reported in the following years (kenawy, 2015). However, the risk of subsequent localized outbreaks of malaria cases exists due to infection of local anopheline mosquitoes by imported cases mainly from Sudan and Africa (Hassan et al., 2003). Moreover, Ismailia populations were infected by Rift Valley Fever virus (Ghoneim and Woods, 1983) with reported outbreaks among humans over the past four decades (Drake et al., 2013).

Integration between remote sensing and geographical information system (GIS) can be used as fast and powerful tools for determination of some environmental factors affecting proliferation of mosquitoes (Sowilem, 2014). Moreover, GIS tools could successfully be utilized to predict the habitat appropriateness, which can help in designing optimal mosquito vector control strategies based on precise spatial/temporal information database (Agarwal et al., 2012). Consequently, most of the developed countries are applying these systems to develop their own levels of policy to mitigate mosquito problems. Furthermore, geospatial mapping by using remote sensing offers the potential to identify larval habitats on a large geographic area that is difficult or impossible using field surveys. Globally, several studies have successfully utilized geospatial techniques (remote sensing and GIS) in environmental studies of mosquito (Hayes et al., 1985; Washino and Wood, 1994; Dale et al., 1998; Hay et al., 1998; Hassan et al., 2003; Li et al., 2006; Palaniyandi and Mariappan, 2012; Hanafi-Bojd et al., 2012; Palaniyandi, 2014, 2015).

Finally, the information about spatial distribution of mosquito species is still unavailable within the study area because of the local travelling difficulty to access this area for research. Even now, conducting field research, near the Suez Canal, often requires special permissions therefore urgent needs for more focused studies are arisen. The main objective of this research is to model the spatial distribution of probable mosquito breeding sites, including non-surveyed and inaccessible areas, at Suez Canal zone by integrating limited field surveys and laboratory identifications of larval mosquito species with remote sensing and GIS techniques.

2. Material and methods

2.1. Study area

The Suez Canal is situated in the northeast of Egypt and extends from Port Said, in the North, to Port Taufiq, near Suez, in the South. Extreme borders of the Canal lie between latitude 29° 5′ N to 31° 10′ N and longitude 32° 18′ E to 32° 35′ E. It connects the Mediterranean Sea at North to the Suez Gulf at South and thus to the Red Sea, as shown in Fig. 1. It is 165 km long and passes through an area of substantial agriculture, industrial and tourism activity. The canal cut through three different lakes; Manzala Lake in the north, Temsah Lake in the middle and Bitter Lakes in the south. The study area is located along the Suez Canal from Port Said, on the northern extremity, to Suez Governorate including the three Suez Canal governorates; Port Said, Ismailia and Suez. The area under investigation occupies 7445.87 km^2 and lies between latitude 29° 30′ N to 31° 30′ N and longitude 32° 10′ E to 32° 40′ E. It is bordered from the north by Mediterranean Sea, west and south by eastern desert, and from the northern east by Sinai Peninsula.

2.2. Survey of mosquito breeding habitats

Initially, mosquito reproduction is successful only if larval habitats stay stagnant for a period equivalent to development of immature stages (Barros et al., 2011). Sites surveyed throughout Suez Canal area included; seepage from the Suez Canal, some irrigation and drainage canals, sewage, cesspools, sabkha land and water logged areas (Table 1, Fig. 2). First field trip was conducted during January 2015, where a number of 31 different localities were surveyed. The survey covered the region from Port Said Governorate to El-Ain El-Sokhna (i.e. South of Suez Governorate). Mosquito larvae were collected using a small ladle (10.5 cm diameter with 90 cm wooden handle). Collected larvae were placed in labeled glass vials containing a fixative solution (70% Ethyl Alcohol) and transported to the laboratory for identification using the Keys of Harbach (1988) and Glick (1992). Procedures and precautions in larval collection were done according to World Health Organization (1975). Surveyed sites were geo-referenced using a hand-held Global Positioning System device (GPS, Magellan 320-USA).

The first field trip was conducted for the purpose of collecting mosquito larvae and identifying the environmental characteristics of mosquito breeding sites (habitat). Based on these characteristics, a cartographic model was built to predict mosquito breeding habitats in the whole study area including the non-surveyed sites. Another field trip was conducted in February 2016 in order to validate the predicted area and ascertain efficiency of the generated model in identifying mosquito breeding habitats. In the second field trip a number of 42 different sites, located within the predicted area, were surveyed.

2.3. Satellite sensor and image preprocessing

Space-borne multispectral Landsat8-OLI image, dated 29th January 2015, was freely downloaded from http://glovis.usgs.gov/. The study area is located in two scenes (path 176, rows 38 and 39) and acquired as raw data (Digital Number, DN). Initially, radiometric calibration and atmospheric correction were applied for each scene separately to correct radiometric errors and spectral distortions in the image, using ENVI V5.1. A georeferenced mosaic was produced, at which the study area was cropped. Finally, water bodies defined as non-stagnant (e.g. Suez Canal) were clipped because they represent non-suitable sites for mosquito breeding as mentioned previously.

2.4. Estimation of NDVI, NDMI and LST

To determine the preferable predictor of mosquito breeding habitats; Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI) and Land surface Temperature (LST) were calculated at mosquito breeding sites. First studied index is NDVI which responds to variations in chlorophyll content, green biomass and canopy water stress. It is important in predicting surface characteristics when the vegetation cover is not too

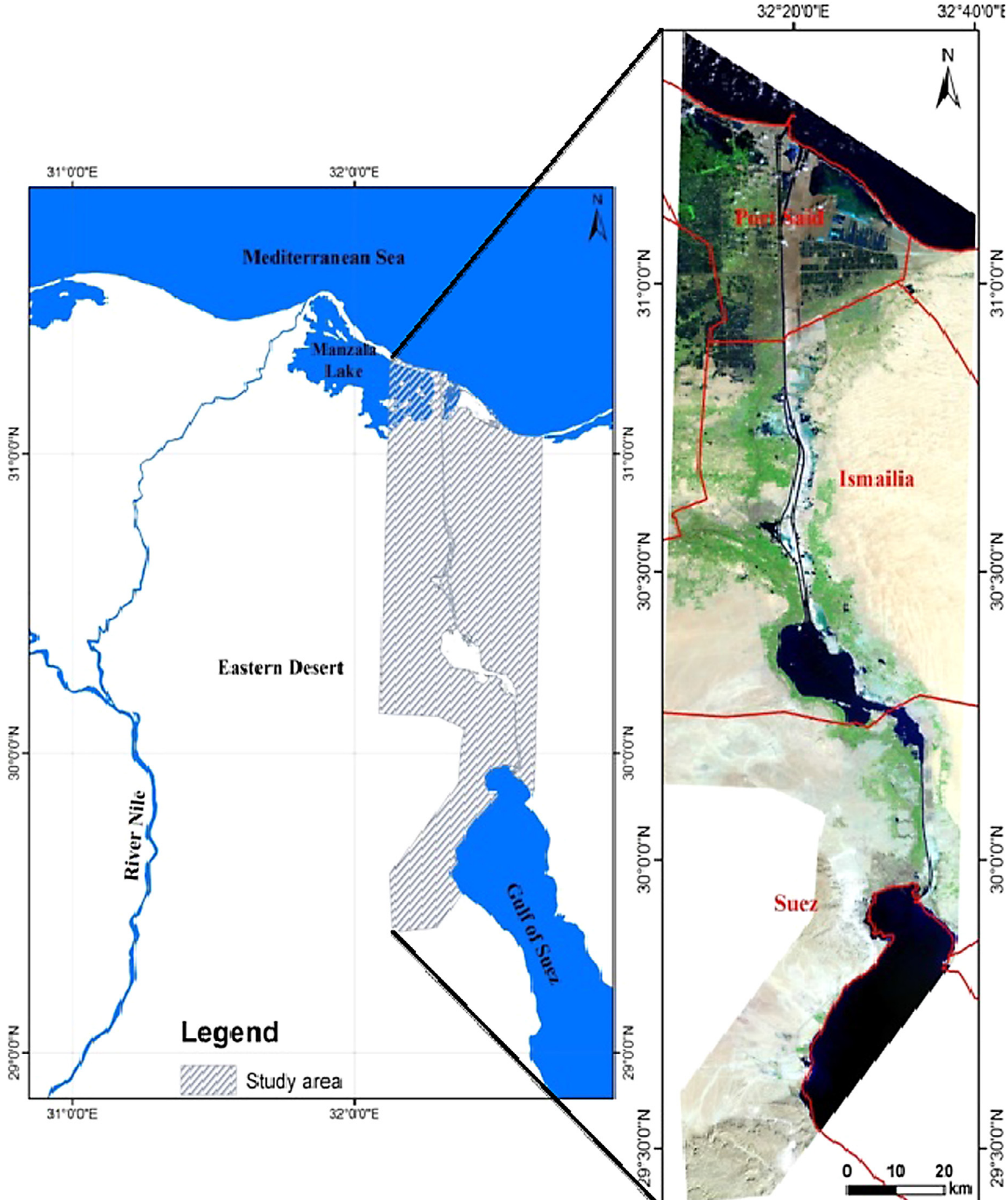

Fig. 1. Location map for the study area.

dense or too sparse (Liang, 2004). ENVI Classic's NDVI uses the standard algorithm and determined using the red and near-infrared (NIR) bands of a given image (Rouse et al., 1973), expressed as follows:

$$NDVI = (NIR - RED)/(NIR + RED)$$

Second studied index is NDMI which correlates with soil moisture. It contrasts near-infrared (NIR) band, which is sensitive to reflectance of leaf chlorophyll and to mid-infrared (SWIR). Values higher than 0.1 indicate to high humidity level, while low levels (close to -1) signify low humidity content (Duran, 2015). NDMI is expressed as follows:

$$NDMI = (NIR - SWIR)/(NIR + SWIR)$$

Finally, LST is an important parameter in physics of earth surface through process of energy and water exchange with atmosphere. This process plays an important role in wide fields of

Table 1
Description of surveyed sites (Jan. 2015).

No.	X	Y	Habitat description
1	32.329722	29.593889	Cesspit, stagnant and turbid water, shaded
2	32.331111	29.591944	Domestic sewage, stagnant, shallow, exposed to sunlight
3	32.335556	29.588333	Small pond, stagnant, turbid, shallow, partially shaded surrounded by dense vegetation, salt land
4	32.345278	29.583889	Small pond, stagnant, partially shaded, surrounded by dense vegetation, green algae
5	32.374444	29.731944	Dry water basins, exposed to sunlight, sabkha land, strong winds
6	32.411944	29.767500	Agricultural drain, slow water flow, exposed to sunlight, strong winds
7	32.438611	29.789722	Area dried up recently, surrounded by dense vegetation
8	32.453333	29.800278	Seepage, shallow, turbid, partially shaded, green algae
9	32.473333	29.929444	Area dried up recently, surrounded by dense vegetation and some date palm
10	32.491111	29.948889	Seepage, stagnant, turbid, exposed to sunlight, surrounded by vegetation, green algae
11	32.511111	29.961111	Large seepage, stagnant, deep, turbid, exposed to sunlight, surrounded by vegetation, sabkha land
12	32.490556	29.996944	Seepage, stagnant, shallow, exposed to sunlight, green algae, surrounded by grasses
13	32.504167	29.979167	Seepage, turbid, deep, exposed to sunlight, surrounded by grasses, salt land
14	32.497778	29.983333	Large seepage, turbid, deep, brown algae, exposed to sunlight, surrounded by vegetation, close to houses
15	32.551389	29.986111	Large seepage, partially shaded, shallow, surrounded by vegetation, close to houses
16	32.551944	30.012778	Domestic wastewater, deep, exposed to sunlight, surrounded by grasses, very close to houses (about 3 m distance)
17	32.546667	30.075833	Large seepage, turbid, deep, exposed to sunlight
18	32.543333	30.101667	Agricultural drain, turbid, deep, green algae, partially shaded, surrounded by vegetation
19	32.520000	30.121944	Agricultural drain, turbid, deep, partially shaded, surrounded by woven plants
20	32.517222	30.124444	Small agricultural drain, turbid, stagnant, partially shaded, surrounded by vegetation (Fruits gardens)
21	32.420000	30.214722	Seepage, turbid, deep, shallow, partially shaded, surrounded by vegetation
22	32.287500	30.469722	Agricultural drain, current water with fishes
23	32.288333	30.467500	Large seepage, turbid water, partially shaded, at a distance about 10 m from houses, sabkha land
24	32.297500	30.483889	Large ponds, covered with water plant, deep, exposed to sunlight, with water bugs, and Odonata
25	32.288056	30.491667	Agricultural drain, turbid, shallow, exposed to sunlight, green algae
26	32.245833	30.548611	Seepage, shallow, turbid water, partially shaded, green algae, surrounded by woven and different plants
27	32.261667	30.722500	Small irrigation canal, deep, clear, shaded
28	32.262222	30.723056	Domestic drain, turbid, domestic wastes, exposed to sunlight, surrounded by different plants
29	32.260833	30.730000	Agriculture drain, turbid, shallow, partially shaded, surrounded by dense woven and other plants
30	32.305278	30.834444	Water logging, stagnant, turbid, shallow, partially shaded, surrounded by vegetation, close to houses, sabkha land
31	32.307778	30.973333	Water logging, turbid water, shallow, partially shaded, green algae, surrounded by different plants

scientific studies; as hydrology, ecology and global change researches. Thermal infrared remote sensing (i.e. Thermal bands) provides a unique method for obtaining information on LST in global and regional scales where most of the sensor's detected energy is directly emitted by land surface (Yu et al., 2014). Following expressions were followed to convert DN values to Temperature (Celsius) for Landsat-8; band 10 (Duran, 2015):

$$L\lambda = Gain * DN + Bias = ((Lmax - Lmin)/255) * DN + Bias$$

$$Reflectance = 0.00033420 * (DN\ of\ B10\ of\ Landsat8)$$

$$Temperature\ (Kelvin) = 1321.08/log(774.89/B10)$$

$$Temperature\ (Celsius) = Temperature\ in\ Kelvin - 273.15$$

where, L_{λ}: spectral radiance at the sensor (watt per steradian per square meter; $W{\cdot}sr^{-1}{\cdot}m^{-2}$), Bias: Lmin.

2.5. Adopted methodology and GIS modeling

The present paper represents a part of research and development project (2014–2016) conducted to develop and enhance cartographic predictive models to locate probable mosquito larval habitats in Suez Canal Zone. In this project, multi-spatial/temporal data (during the period 2014–2016) and geographic information system (GIS) was integrated. The present paper explores potentiality and efficiency of the predictive model generated in January 2015 (winter model) to detect mosquito breeding habitats in winter at the whole Suez Canal Zone.

Remote sensing and field surveys provided the required spectral and in-situ information to this research (Fig. 3). NDVI and NDMI were derived from multispectral bands of the Landsat8 image, while LST was calculated from thermal band (Band 10). Mosquito larval species were identified in the lab where ID was assigned for each analysis then a GIS thematic layer, attributed with the analyses, was created.

Environmental variables (i.e. NDVI, NDMI and LST), at mosquitoes breeding sites, were extracted to characterize mosquito breeding habitats. On basis of mosquito habitat characterization, the produced raster layers (NDVI, NDMI and LST) were reclassified. Simply, each cell in the study area has a value for each input criteria (NDVI, NDMI, LST). Using the weighted overlay tool in ArcGIS environment, it can weigh the values of each dataset and combine them to create suitability map that identify the potential locations for mosquito breeding (Fig. 4).

Urbanization facilitates the proliferation of different mosquito species that most often transmit pathogens to humans (Wilcox and Gubler, 2005; Juliano and Lounibos, 2005). The most direct effect of urbanization is the creation of habitat (e.g., artificial containers, storm water pools) that supports the development of immature stages (larva and egg) of some mosquito species (Leisnham and Slaney, 2009). On this basis, a thematic layer of urban areas was used to clip mosquito predicted areas associated with residential zone which were categorized as very high risk area using ArcGIS V. 10.1. In the present study, a radius of two kilometres around the urban area served to determine the areas at risk of mosquito proliferation (Dale and Morris, 1996; Dale et al., 1996; Hay, 1997; Hassan and Onsi, 2004; Palaniyandi, 2004; Palaniyandi and Mariappan, 2012).

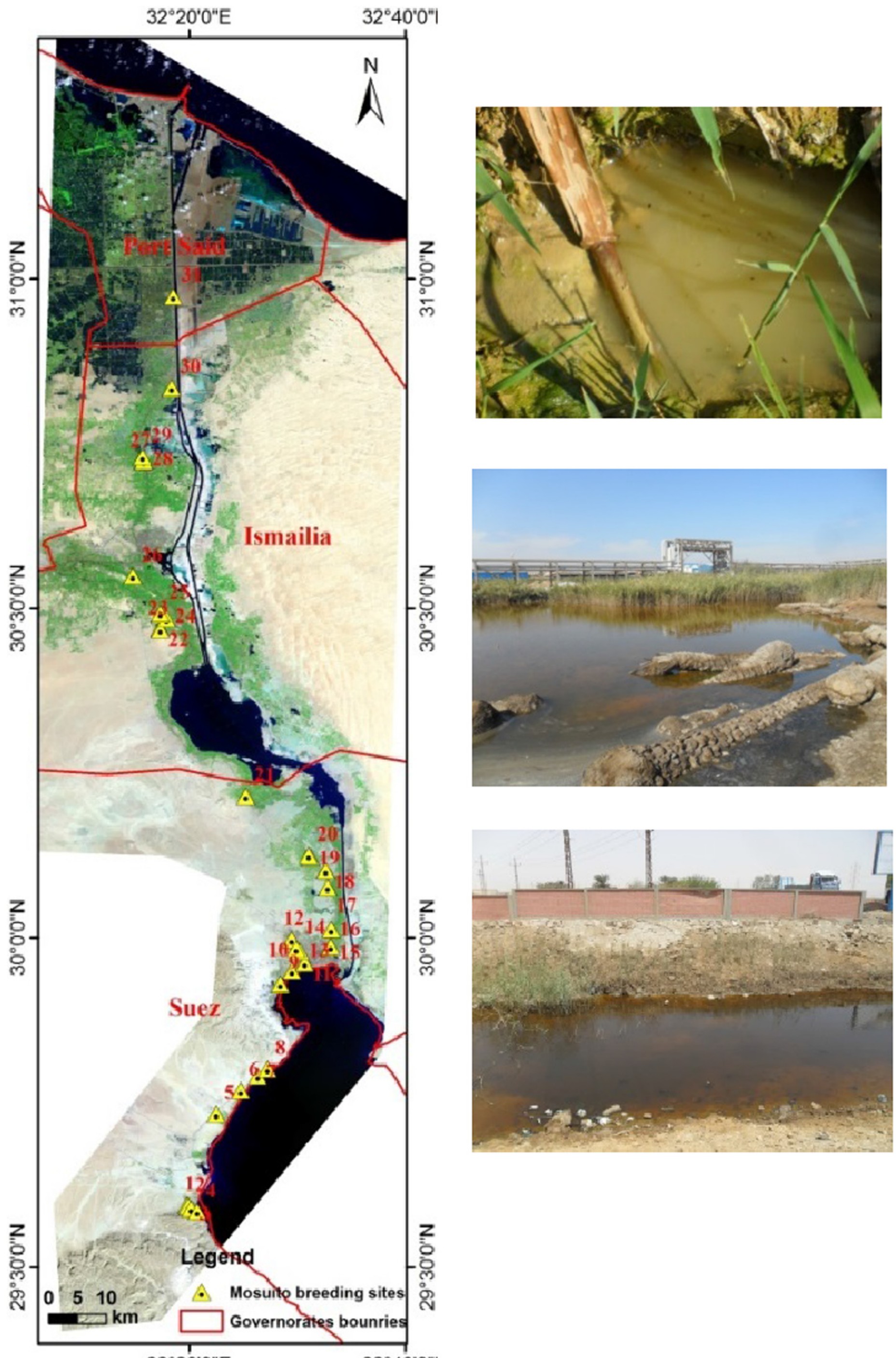

Fig. 2. Mosquito breeding sites surveyed in Jan. 2015; right pictures captured from the field.

3. Results and discussion

3.1. Mosquito larval abundance and species composition

In January 2015, a total number of 31 different localities were surveyed at the western banks of Suez Canal Zone. Mosquito larvae were detected in 17 sites (+ve) of the total sites surveyed. A total number of 698 mosquito larvae belonging to 4 genera and 7 species were recorded. The species recorded include *Culex pipiens, Culex perexiguus, Culex pusillus, Culiseta longiareolata, Ochlerotatus caspius, Ochlerotatus detritus and Anopheles multicolor*.

The most common two species detected were *Culex pipiens and Ochlerotatus detritus* recording 362 larvae (52%) and 244 larvae (35%), respectively (Table 2, Fig. 5). It was found that *Culex pipiens* prefers sites of high human population densities and breed in artificial containers close to human settlements (Kalluri et al., 2007; Tran et al., 2013) or contaminated ponds (Amr et al., 1997; Al-Khalili et al., 1999; Knio et al., 2005; Ammar et al., 2012). This indicates to the presence of the main filariasis vector in most of the breeding habitats surveyed (Harb et al., 1993). Conversely, the least abundant two species were *Anopheles multicolor* and *Ochlerotatus caspius* recording 5 larvae (0.716%) and 8 larvae (1.146%), respectively.

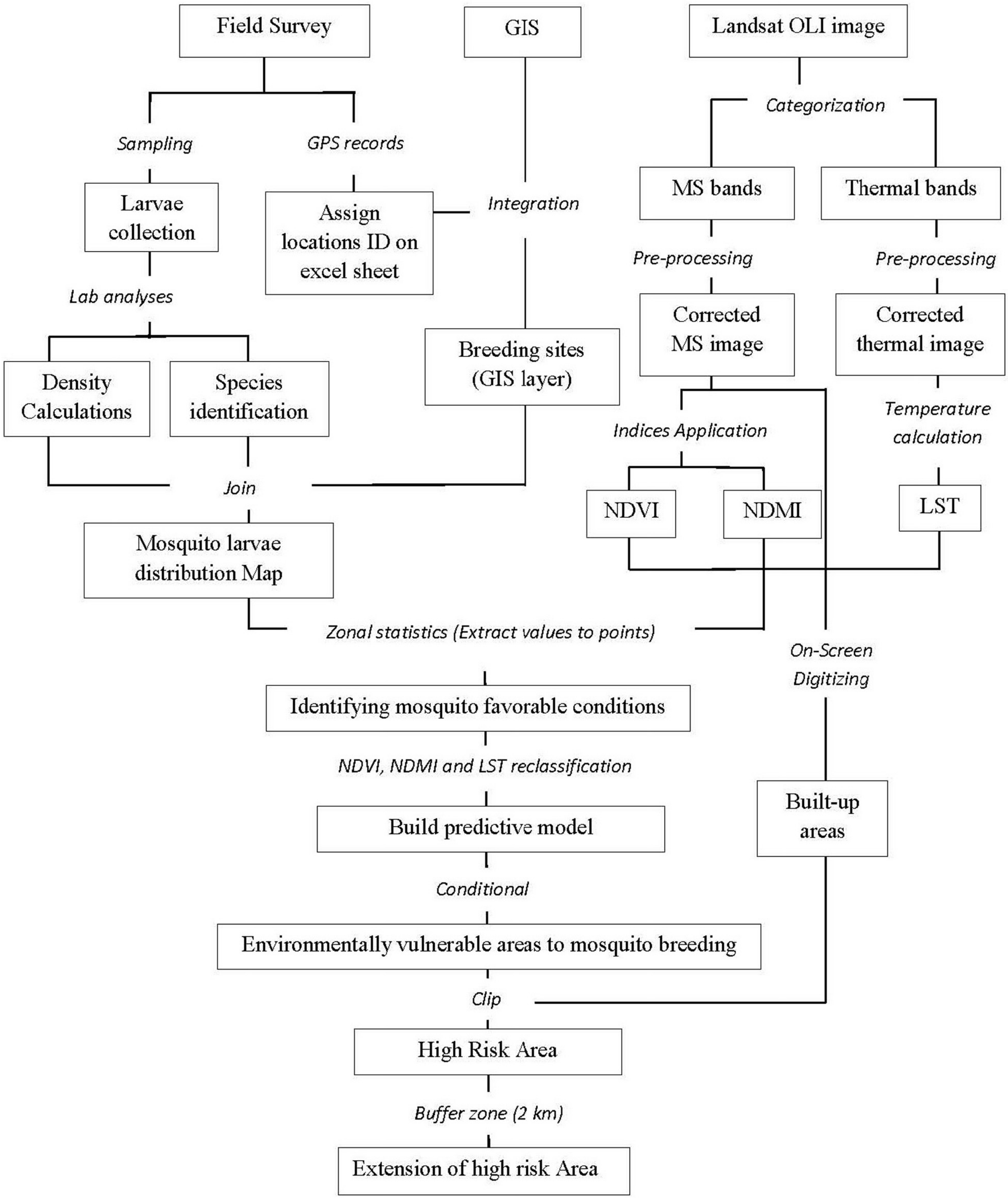

Fig. 3. Flow chart showing the methodology adopted in identifying the areas under environmental risk of mosquito proliferation.

Mosquito breeding sites, in Suez Canal Zone, were commonly found in association with shallow contaminated water bodies and vegetation covered areas (sparse or dense, natural or cultivated, merged or submerged). Breeding sites recorded were observed as partially exposed to sunlight. Specifically, *Culex pipiens* and *Culex perexiguus* were found associated with domestic sewage and seepage areas. On the other hand, *Anopheles multicolor, Ochlerotatus caspius and Ochlerotatus detritus* proliferated in brackish water bodies and sabkha lands. The present finding are similar to observations given by El-Said and Kenawy (1983), Bahgat et al. (2004) and Abdel-Hamid et al. (2011).

In Egypt, *Culex pipiens* and *Culex perexiguus* are the main vectors of human Filariasis (Gad et al., 1987), Rift valley fever virus (Hoogstraal et al., 1979; Meegan et al., 1980) and West Nile virus

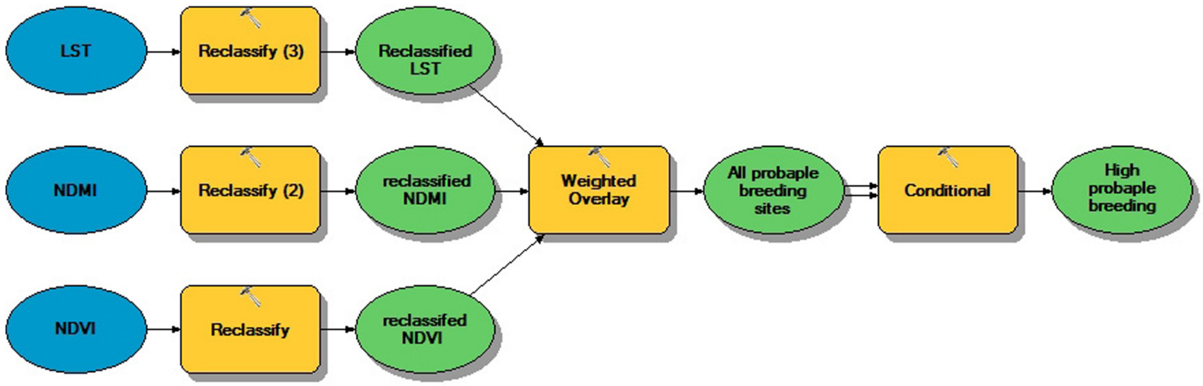

Fig. 4. Cartographic model for predicting mosquito breeding habitats.

Table 2
Relative abundance of mosquito larval species in different collection sites (Jan. 2015).

Species	Number of larvae	Percent%
Culex pipiens	362	51.862
Culex perexiguus	46	6.590
Culex pusillus	14	2.006
Anopheles multicolor	5	0.716
Culiseta longiareolata	19	2.722
Ochlerotatus caspius	8	1.146
Ochlerotatus detritus	244	34.957
Total	698	100.000

(Hurlbut et al., 1956; Darwish and Hoogstraal, 1981). *Anopheles multicolor* is suspected as a vector of Malaria (Gad et al., 1964; Zahar, 1974; El-Said et al., 1986; Kenawy et al., 1986a; Kenawy, 1988, 2015). *Ochlerotatus caspius* was incriminated to transfer Rift valley fever virus through 1977–1993 epidemics (Gad et al., 1987; Turell et al., 1996).

3.2. Environmental variables associated with mosquito proliferation

Survival and distribution of mosquitoes are significantly influenced by different environmental variables as humidity, temperature, vegetation and availability of suitable larval habitats (Martens et al., 1999; Molyneux, 1998, 2003; Grillet, 2000; Wamae et al., 2010; Afrane et al., 2012; Berger et al., 2012). These variables are important for both diseases transmission and for maintaining breeding sites for the mosquito vector (Crombie et al., 1999).

In the present study, LST, NDVI and NDMI were used to identify the environmental characteristics of mosquito breeding habitats. NDVI is related to disease transmission and abundance (Brownstein et al., 2002; Diuk-Wasser et al., 2006; Brown et al., 2008). Patz et al. (1998) and Eisele et al. (2003) demonstrated that number of breeding habitats and NDVI are positively correlated with soil moisture (NDMI). Moreover, temperature (LST) changes also affect the behaviour and geographical distribution of mosquito. The optimum temperature for mosquitoes is 25–27 °C and

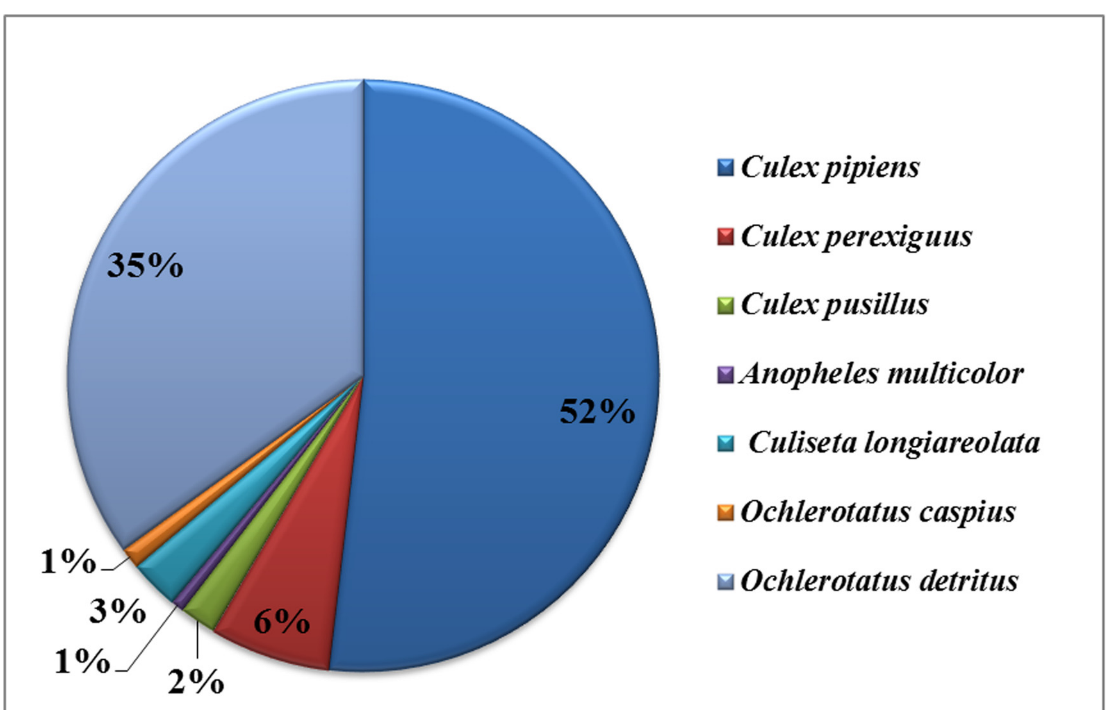

Fig. 5. Percent of mosquito larvae at Suez Canal area (Jan. 2015).

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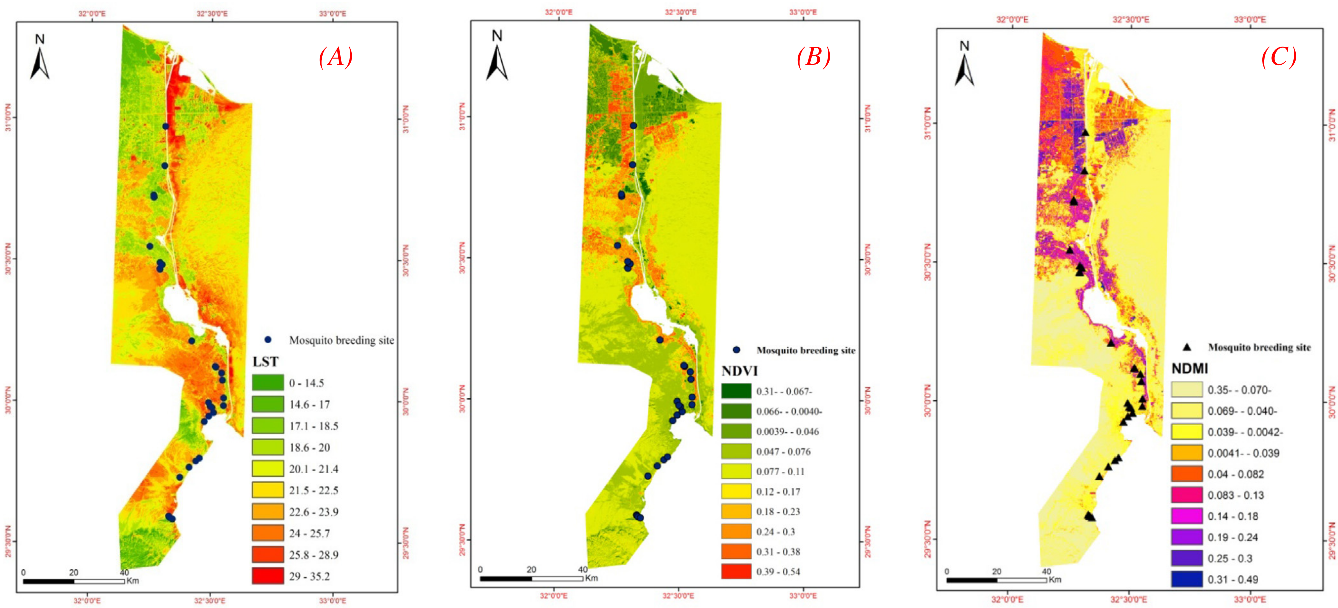

Fig. 6. Spatial distribution maps of environmental variables; LST °C (A), NDVI (B) and NDMI (C).

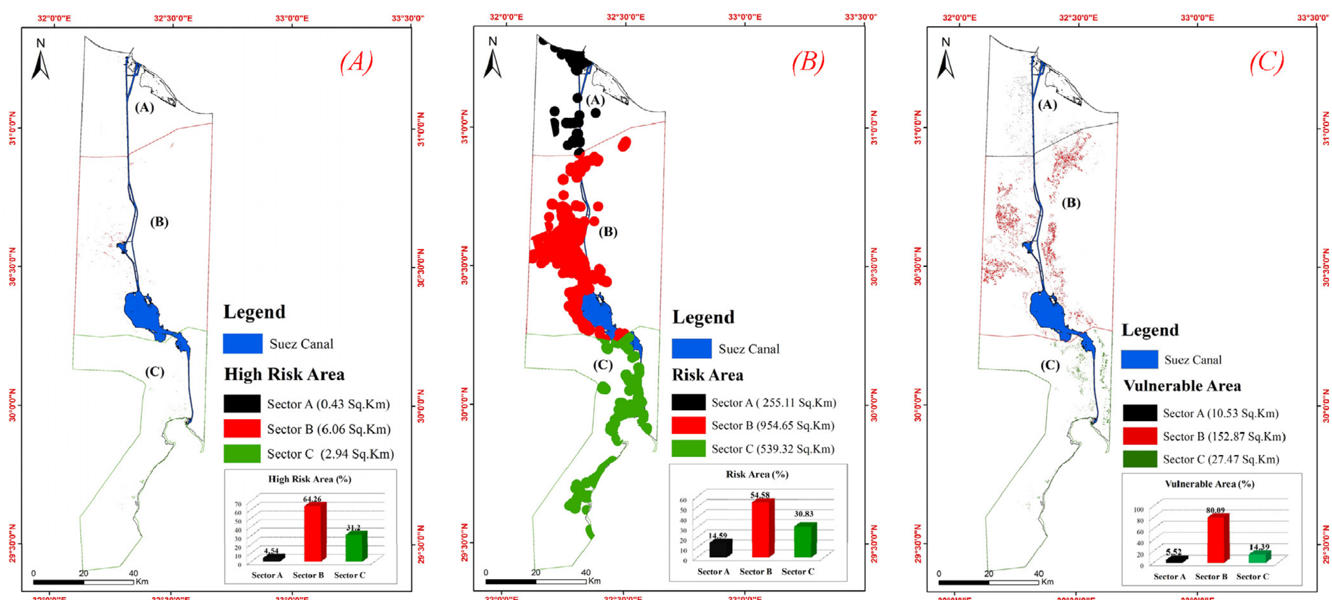

Fig. 7. Areas under environmental risk of mosquito proliferation; High Risk Area (A), Risk Area (B) and Vulnerable Area (C).

the maximum temperature for both vectors and parasites is 40 °C (Martens et al., 1995).

Spatial distribution map of LST showed a temperature range between 14.5 to 35.2 °C. High temperature levels were found in barren land and build-up areas (e.g. Port Fouad, Ain Sokhna and part of El-Suez). However, low temperature levels were observed in the Mediterranean Sea Coastal area (Fig. 6: A). On the other hand, NDVI map showed a range fluctuating from −0.31 to 0.54 where vegetated areas (i.e. NDVI > 0.2) were distributed in separate parts along the Canal mainly at Ismailia Governorate. Sparse natural vegetation was distributed in eastern and western parts of the study area (Fig. 6: B). Spatial distribution map of NDMI showed a range between −0.34 and 0.49 where low levels (Close to −1) were reported in barren land areas while the high humidity levels (>0.1) were mostly observed in vegetation covered areas (Fig. 6: C).

Levels of NDVI, NDMI and LST at mosquito breeding sites were, then, extracted to identify the optimum environmental characteristics of mosquito breeding habitats. In mosquito breeding sites, NDVI ranged from 0 to 0.18 (Sparse vegetation), NDMI from −0.06 to 0.13 and LST from 19.1 °C to 25.6 °C. Likewise, correlation coefficient was calculated to assess the statistical relationship between these parameters and mosquito larval density. Significant positive correlations were recorded between mosquito larval density and the environmental variables studied; LST (0.717), NDMI (0.816) and NDVI (0.546). Considering these relationships, the model was generated to predict the areas under environmental risk of mosquito proliferation at the whole study area.

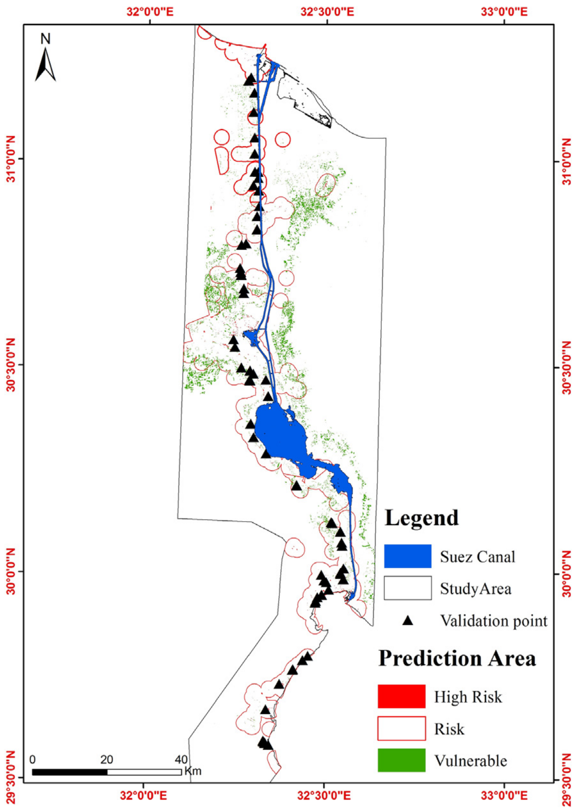

Fig. 8. Field verification points surveyed in Feb. 2016, Suez Canal Zone.

3.3. Predictive model development and validation

Number of studies has been conducted, at Suez Canal Zone, to identify mosquito species and characterize breeding habitats using field surveys and lab analyses (e.g. Kenawy and El-Said, 1990; Kenawy et al., 1996; Abdel-Hamid et al., 2011; Ammar et al., 2013). In Egypt, few studies have been performed on mosquito proliferation and habitats characterization using geospatial techniques (e.g. Hassan et al., 2003; Fawaz, 2012; Sowilem, 2014). The present study represents one of the initial attempts to detect mosquito breeding habitats and predict the areas under environmental risk of mosquito proliferation using integrated remote sensing/GIS techniques in Suez Canal Zone.

A GIS simple cartographic model was generated based on the corresponding values of NDVI, NDMI and LST at mosquito breeding sites which define the optimal environmental characteristics for mosquito proliferation at Suez Canal Zone, Egypt. Results of the model showed that mosquito breeding habitats are distributed in separate parts along the Suez Canal. In order to assess the predicted habitats, the study area was categorized from North to South to 3 sectors; Sector A (Northern parts, mostly located in Port Said Governorate), Sector B (Central part, mostly located in Ismailia Governorate) and Sector C (Southern parts, mostly located in Suez Governorate). Sector B recorded the highest predicted levels of the high risk, risk and vulnerable areas; 6.06 km^2 (64.26%), 954.65 km^2 (54.58%) and 152.87 km^2 (80.09%), respectively (Fig. 7: A–C). It was observed that mosquito prefer the partially shaded habitats throughout Ismailia Governorate which is in agreement with Abdel-Hamid et al. (2011). Conversely, Sector A recorded the lowest predicted mosquito habitats where minimum high risk, risk and vulnerable areas were detected; 0.43 km^2 (4.54%), 255.11 km^2 (14.59%) and 10.53 km^2 (5.52%), respectively. Sector C recorded the second expected area for mosquito proliferation at Suez Canal Zone; high risk 2.94 km^2 (31.20%), risk 539.32 km^2 (30.83%) and vulnerable area 27.4 km^2 (14.39%).

Several studies, all over the world, have used remote sensing and GIS techniques for mosquito habitat identification (e.g. Hayes et al., 1985; Linthicum et al., 1987; Masuoka et al., 2003; Townshend et al., 2000; Khormi and Kumar, 2012; Cianci et al., 2015). However, few studies have considered the result verification. In the present study, the generated model was assessed and validated. This was achieved by conducting a field survey in Feb. 2016 to 42 different sites located within the predicted area (i.e. high risk, risk and vulnerable areas) as shown in Fig. 8. Out of the 42 surveyed sites, a number of 4 sites were found negative for mosquito larvae and 5 sites were not detected correctly. The rest of 34 sites were found positive for mosquito larvae where 6 sites were located in the high risk area, 24 sites in the risk area and 4 in the vulnerable area (Table 3, Fig. 8). This means that majority of the positive sites were located within the risk area.

In the present study, the selected environmental variables (NDVI, NDMI and LST) have led to satisfactory results related to mosquito larval habitat identification and risk area mapping. The model achieved accuracy 80.95% which approaches 100% at sites

Table 3
Predictive model validation based on field survey (Feb. 2016).

Validation points	Field validation	Model's predicted category	Validation points	Field validation	Model's predicted category
1	+ve	Vul.	22	+ve	R
2	+ve	Vul.	23	−ve	R
3	+ve	Vul.	24	−ve	R
4	+ve	Vul.	25	+ve	R
5	−ve	HR	26	+ve	False
6	+ve	HR	27	+ve	False
7	+ve	R	28	+ve	False
8	+ve	HR	29	+ve	False
9	+ve	HR	30	+ve	R
10	+ve	HR	31	+ve	R
11	+ve	R	32	+ve	R
12	+ve	R	33	+ve	R
13	+ve	R	34	+ve	R
14	+ve	R	35	+ve	R
15	+ve	R	36	+ve	HR
16	+ve	R	37	+ve	R
17	−ve	R	38	+ve	R
18	+ve	R	39	+ve	R
19	+ve	R	40	+ve	False
20	+ve	R	41	+ve	R
21	+ve	R	42	+ve	R

Abbreviations: HR: high risk area, R: risk area, Vul: vulnerable area, + ve: positive site, −ve: negative site, False: not detected correctly.

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ascertained by in-situ checks. Despite the presence of some validation points outside scope of the predicted area, they fall very close to the area under risk of mosquito breeding. This indicates that these sites may also be subjected to the transmission of mosquito-borne diseases. This means that the whole predicted area is located under environmental risk of mosquito proliferation which needs an application of appropriate control strategy. Finally, the precise spatial distribution mapping of mosquito breeding habitats is necessary for cost-effective control of vectors in addition to facilitate assessment of risk induced from diseases transition (Dale et al., 1998; Thomson and Connor, 2000; Vanwanbeke et al., 2007).

4. Conclusion

It can generally be concluded that remote sensing and GIS techniques offer the necessary requirements for studying the environmental variables associated with mosquito breeding habitats, thus mapping risk areas. GIS modeling proved strong success in identifying the relationships between occurrence of mosquito (presence/absence) and environmental data. Extrapolation of the data allows prediction of mosquito occurrences for all un-sampled locations within Suez Canal area. It was possible to verify that *Culex pipiens* and *Ochlerotatus detritus* were the most common species in Suez Canal Zone. Moreover, Ismailia represents the highest Governorate located under environmental risk of mosquito proliferation at Suez Canal Zone. Although the model produced good results, it is recommended to be enhanced by combining more spectral indices (i.e. NDSI and MNDWI) in addition to soil and water characteristics in order to incorporate more environmental variables in the future work. A specific GIS model, for each mosquito species, is also recommended to be generated

Conflict of interest

No conflict of interest.

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