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Spatial distribution modeling of *Stegomyia aegypti* and *Culex tritaeniorhynchus* (Diptera: Culicidae) in Al-bahah Province, Kingdom of Saudi Arabia

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Abstract. Dengue hemorrhagic fever and Rift Valley fever are the most important mosquito-borne diseases in the Kingdom of Saudi Arabia. The characteristic habitat requirements of *Stegomyia aegypti* and *Culex tritaeniorhynchus*, the two mosquito vectors will help in the identification of "high risk" areas in their development. Species distribution modelling was assessed by using MaxEnt software combined with geographical information systems (GIS) to predict suitable larval habitats for these two vectors and develop potential risk maps that can be used for their targeted control. Climate and topographical data layers from Worldclim and larval occurrence records were used to model these two vectors. The results showed that suitable habitats of *St. aegypti* are widely distributed only in the central region and *Cx. tritaeniorhynchus* were in the central and southwestern parts of Al-Bahah Province. The highest predictive power was shown by topographical variables in *St. aegypti* modeling and the minor contributions were shown by precipitation and temperature related variables. The maximum contribution was shown by temperature related variables and minor contribution was shown by topographical and precipitation related variables in *Cx. tritaeniorhynchus* modeling. Linear regression model indicates non significant correlation between TDS/pH and species abundance of these two mosquitoes.

INTRODUCTION

Mosquitoes are important arthropods vectors of several diseases in the world. There are increasing reports on different vector borne diseases in different parts of the world (Nakhapakorn & Tripathi, 2005). In the Kingdom of Saudi Arabia (KSA), several studies are available on mosquitoes (Alahmed *et al.*, 2011; Abdoon & Alsharani, 2003; Ayyub *et al.*, 2006; Khater *et al.*, 2013; Sallam *et al.*, 2013; Al Ashry *et al.*, 2014). KSA has approximately 11% of the world vector-borne disease burden (WHO, 2004), for example: Dengue fever (DF) (Fakeeh & Zaki, 2001; 2003; Ayyub *et al.*, 2006; Khan *et al.*, 2008), filariasis (Hawking, 1973), malaria (Warrel, 1993; Al-Seghayer *et al.*, 1999; Abdoon & Alsharani, 2003) and Rift Valley fever (RVF) (Jupp *et al.*, 2002; Miller *et al.*, 2002; Al-Hazmi *et al.*, 2003; Balkhy and Memish, 2003; Madani *et al.*, 2003). RVF and DF are the major arboviral diseases in the Kingdom (Fakeeh and Zaki, 2001; Jupp *et al.*, 2002; Miller *et al.*, 2002). RVF outbreaks were reported since 2000 in southwestern region of KSA and *Culex tritaeniorhynchus* Giles is the confirmed vector (Jupp *et al.*, 2002; Miller *et al.*, 2002). DF outbreaks were first reported in Jeddah and *Stegomyia aegypti* (L) is the confirmed vector (WHO, 2004; El-Badry and Al-Ali, 2010).

Different environmental and bioclimatic factors are responsible for the distribution of mosquito vectors. The combination of these factors are responsible for providing suitable environment for vectors growth and establishment of diseases. Targeted control of disease carrying vectors are worthwhile to conventional control (Charlwood *et al.*, 2003). Recently, different statistical and geographical information system technologies have been applied for the identification of "high risk" areas of vectors and their possible controls (Li & Wang, 2013; Cardoso-Leite *et al.*, 2014). In KSA, maximum entropy modeling and GIS technologies have been used for identification of "high risk" areas of RVF and malaria vectors distribution (Sallam *et al.*, 2013; Alahmed *et al.*, 2015).

In Al-Bahah Province, important mosquito disease vectors such as *Cx. tritaeniorhynchus* and *St. aegypti* have been previously reported (Alahmed *et al.*, 2010). However, no spatial distribution studies using GIS are available for such important mosquito vectors. Presently, no cases of mosquito vector borne diseases has been reported in Al-Bahah Province, but the potential of disease outbreaks is high.

The main objective of this study is to identify the "high risk" areas for the larval habitat of the two mosquito vectors in order to direct and focus their control efforts.

MATERIAL AND METHODS

Study area

This study was conducted in Al-Bahah Province (longitudes 41° to 42°, and latitudes 19° to 21°), located in the southwestern region of KSA (Figure 1) between Makkah and Asir with an area of 12,000 km^2 and a population of 500,000 inhabitants (Saudi Geological Survey, 2012). There are two sectors in Al-Baha Province, (1) Al-Sarah (highland) including four districts: Al-Aqiq, Al-Mandaq, Al-Qura and Baljurashi and (2) Tihama (low land) including only two districts: Al-Mekhwa and Qelwa. Elevation varies between 1,500 and 2,450 m above sea level in Al-Sarah sector (Figure 2). The annual relative humidity (RH) varies between 52% and 67%, and 23ºC and 12ºC, are the maximum and minimum temperatures, respectively (El-Hawagry *et al.*, 2013).

Collection and Identification of mosquito larvae

Mosquito larvae were collected for 11 months from December 2013 to November 2014. All breeding sites were sampled, and the most potential and typical habitats were selected in elevated and lower areas. A standard 350 ml plastic dipper was used for larval collections. The coordinates of the collection sites were taken by global positioning system (GPS) (Garmin, eTrix). After collection all mosquito larvae were preserved in 80% alcohol. Puri's medium was used for mounting of late third or fourth instar larvae. Species were identified using keys of Alahmed *et al.* (2011).

The total dissolved salts (TDS) and pH of the water samples were determined using TDS and pH meters immediately after sampling. The effect of these two chemical factors on the abundance (% collected) of *Cx. tritaeniorhynchus* and *St. aegypti* was examined by a linear regression model (LM). The slopes (regression coefficients) of the regression equations were tested for deviation from zero by t-test. Such effect has been studied for the collections before modeling and from field validation points. The statistical software SPSS package version 17 was used (SPSS Inc., Chicago, Illinois, US).

Modeling procedures, performance and evaluation

For the characterization of mosquito larval habitats, a total of 26 topographical (www.diva-gis.org) and bioclimatic layers (11 layers of temperatures and 8 precipitation indices) (Table 1) were obtained from WorldClim database ver. 1.4 (www.worldclim.org) (Hijmans *et al.*, 2005). Some of the land use-land cover (LULC) variables influencing the distribution of mosquito vectors were included in our model such as roads (Ahmad *et al.*, 2011) of different types (vehicle track, primary unpaved, secondary unpaved, secondary paved) which represent the level of urbanization, vegetation, soil, and dams.

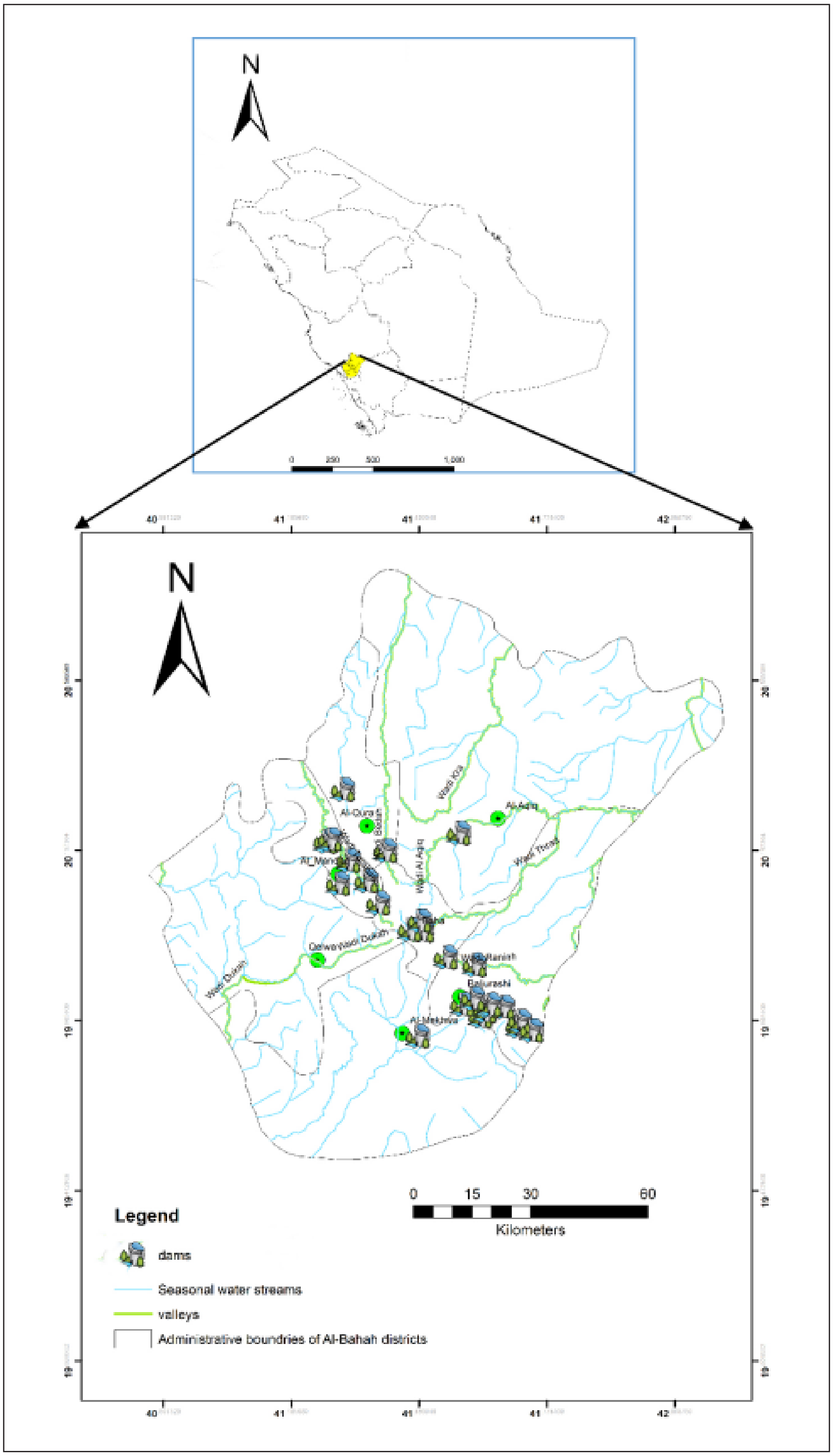

Figure 1. Administrative boundaries of the districts of Al-Bahah Province, Saudi Arabia with major streams, valleys and dams

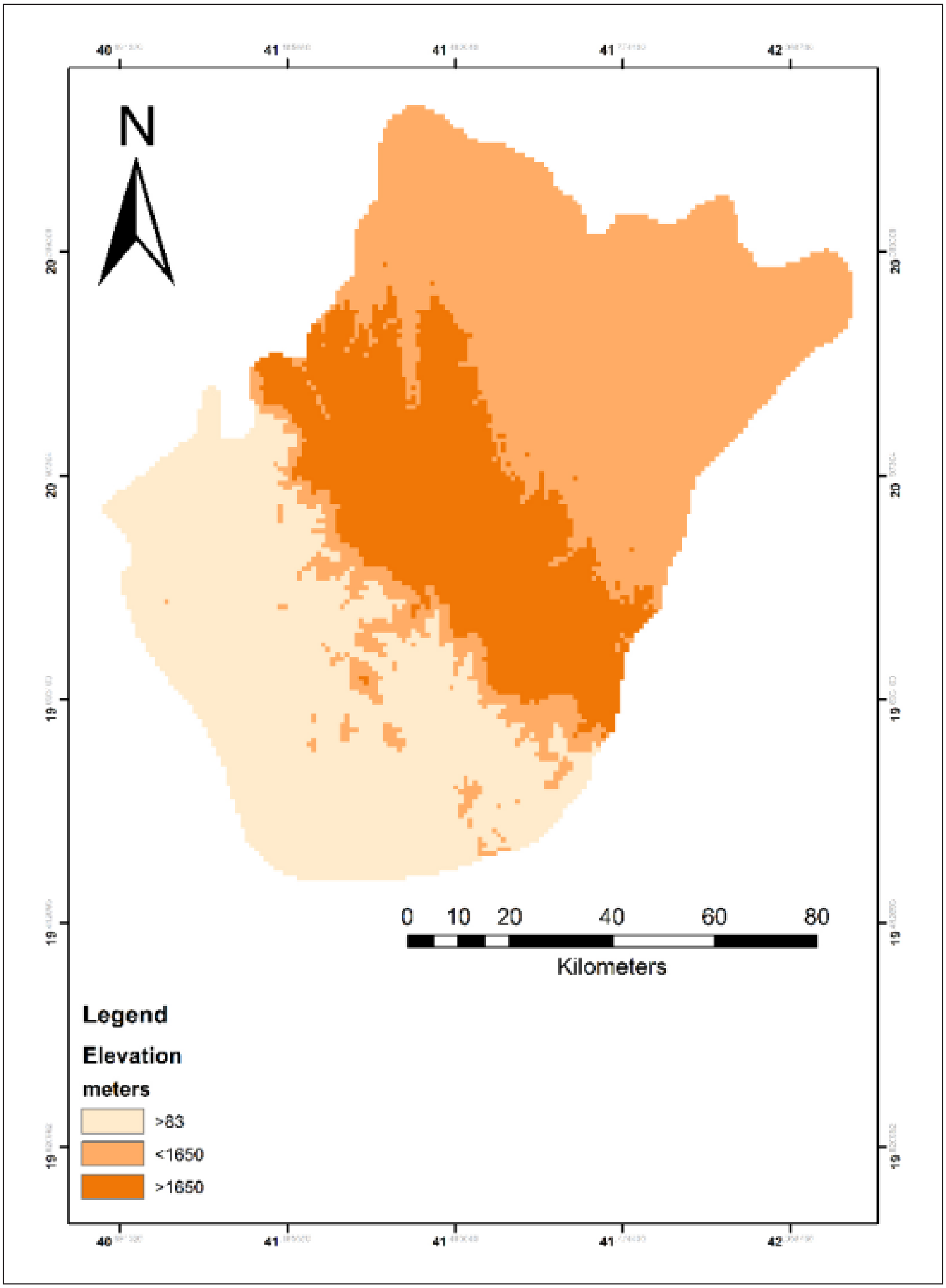

Figure 2. Al-Bahah Province showing elevations above sea level

Table 1. Environmental and topographical variables

Variable	Description
bio1	Annual mean temperature
bio2	Mean Diurnal Range (Mean of Monthly (max temp-min temp)
bio3	Isothermality (bio2/bio7) (*100)
bio4	Temperature seasonality (standard deviation *100)
bio5	Max temperature of warmest month
bio6	Min temperature of coldest month
bio7	Temperature Annual Range (BIO5-BIO6)
bio8	Mean temperature of wettest quarter
bio9	Mean temperature of driest quarter
bio10	Mean temperature of warmest quarter
bio11	Mean temperature of coldest quarter
bio12	Annual precipitation
bio13	Precipitation of wettest month
bio14	Precipitation of driest month
bio15	Precipitation seasonality (Coefficient of variation)
bio16	Precipitation of wettest quarter
bio17	Precipitation of driest quarter
bio18	Precipitation of warmest quarter
bio19	Precipitation of coldest quarter
slope	Slope
aspect	Aspect ratio
altitude	Altitude in degrees
water streams	Streams
roads	Different types of roads
soil	Soil types
dams	Dams

The spatial resolution of these bioclimatic/topographical layers is at 30 arc-seconds (~1 km). All these bioclimatic layers were clipped to match the dimension of Al-Bahah Province and saved in ASCII grid format for using in MaxEnt. For clipping these layers, model builder tool of ArcGIS software v. 10 was used.

The Species distribution modeling was assessed by using MaxEnt software ver. 3.3. The estimation performance of the model was determined by area under the curve (AUC) values of receiver operating characteristics (ROC) curves (Phillips *et al.*, 2006). The collected data was used for training (Pearson *et al.*, 2007; Peterson and Shaw, 2003). Predictive performances of all the variables were determined by jackknifing approach (leave-one-out procedure) in Maxent (Pearson *et al.*, 2007). Moreover, for the confirmation of accuracy of the two models, field validation trips were made to cover all sites with “very high”, “high”, “medium”, “low” and “very low” risk of mosquito larval distribution.

RESULTS

A total of 2,172 mosquito larvae were collected from 111 sites of which, 63 (56.75%) sites were positive. Larvae of *St. aeypti* and *Cx. tritaeniorhynchus* were found to represent 16.44% and 14.5% respectively. The ranges of TDS and pH of the breeding water were 996-1926.4 ppm (parts per million) and 6.4-8.8, respectively. Analysis revealed that the abundance (% collected) of both *St. aegypti* and *Cx. tritaeniorhynchus* larvae were directly related to TDS/pH (slope = 0.22 and 0.2922 respectively) for the two species (P< 0.01).

Ecological niche modeling of *St. aegypti* and *Cx. tritaeniorhynchus* vectors

There were 10 & 17 occurrence records for *St. aegypti* and *Cx. tritaeniorhynchus*, respectively. The spatial model was performed for these two vectors. The predictive performance for training was found high with an AUC = 0.922 for both *St. aegypti* and *Cx. tritaeniorhynchus*. The fractional predicted areas, at 10 percentile training presence were 0.187 & 0.328 and the training omission rates were 0.100 & 0.062 for *St. aegypti* and *Cx. tritaeniorhynchus*, respectively. These points were classified as significantly better than random (P<0.05).

Among the 26 bioclimatic and topographic variable layers 8 for *St. aegypti* and 14 for *Cx. tritaeniorhynchus* were found to contribute in spatial prediction of these larvae (Table 2). A Jackknife test showed that the contributions were: altitude (38.1%), precipitation related variables (21.8%) and temperature related variables (1.4 %) in the modeling of *St. aegypti* (Table 2). For *Cx. tritaeniorhynchus*, the temperature related variables contribution was maximum (51.1%) in the modeling. The precipitation related variables contribute 9.9% and the other variables as slope, streams, soil, road and aspect ratio contributions were 28%, 5.6%, 5%, 0.2% and 0.2%, respectively.

The predictive suitable map of *St. aegypti* (Figure 3) shows "very high" risk areas present at the middle of Al-Bahah Province mostly covering Al-Bahah district, Al-

Table 2. The percentage contribution of the total 26 climatic, topographic and ecological layers in predicting spatial distribution of *St. aegytpi* and *Cx. tritaeniorhynchus* in Al-Bahah Province Saudi Arabia

Species	Variable	Description	% Contribution
St. aegypti	altitude	Elevation	38.1
	soil	Soil	22
	slope	Slope	16.7
	bio19	Precipitation of coldest quarter	8.4
	bio14	Precipitation of driest month	8.2
	bio13	Precipitation of wettest month	3.1
	bio16	Precipitation of wettest quarter	2.1
	bio9	Mean temperature of driest quarter	1.4
Cx. tritaeniorhynchus	bio6	Min. temperature of coldest month	34.4
	slope	Slope	28
	bio9	Mean temperature of driest quarter	15.7
	bio19	Precipitation of coldest quarter	7.6
	streams	Streams	5.6
	soil	Soil	5
	bio13	Precipitation of wettest month	1
	bio5	Max. temperature of warmth month	1
	bio14	Precipitation of driest month	0.6
	bio17	Precipitation of driest quarter	0.4
	bio16	Precipitation of wettest quarter	0.3
	road	Different types of roads	0.2
	aspect	aspect ratio	0.1
	bio12	Annual precipitation	0.1

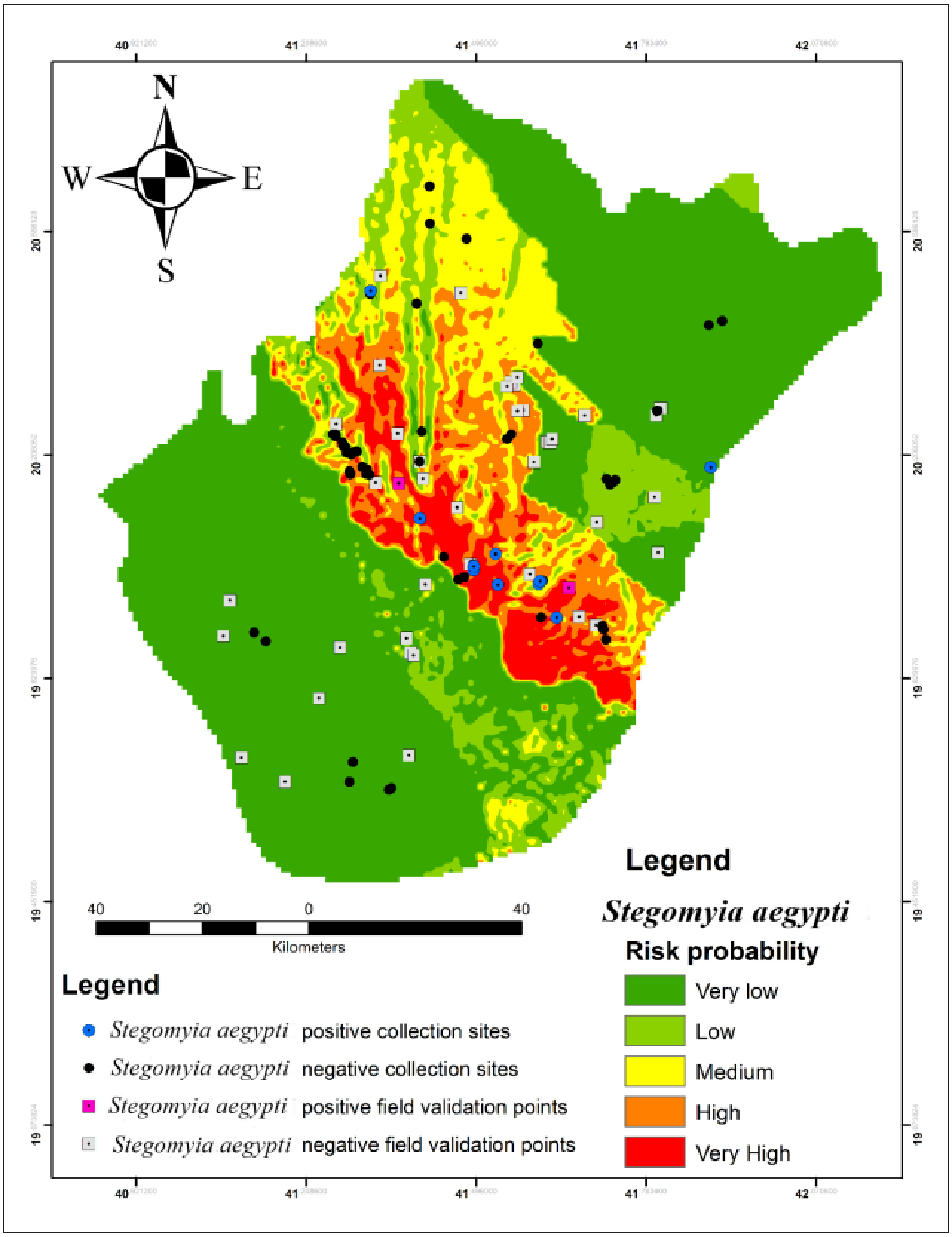

Figure 3. Risk probability distribution map for *St. aegypti* in Al-Bahah Province, Kingdom of Saudi Arabia

Mandaq, Al-Qura, Baljurashi and Al-Aqiq areas. The predictive risk map (Figure 4) shows that the "very high" risk area for *Cx. tritaeniorhynchus* distribution is present in both sectors of Al-Sarah and Tihama. In Tihama sector, Al-Mekhwa district is at more risk as compared to Qelwa district. In Al-Sarah sectors, all four districts are at high risks.

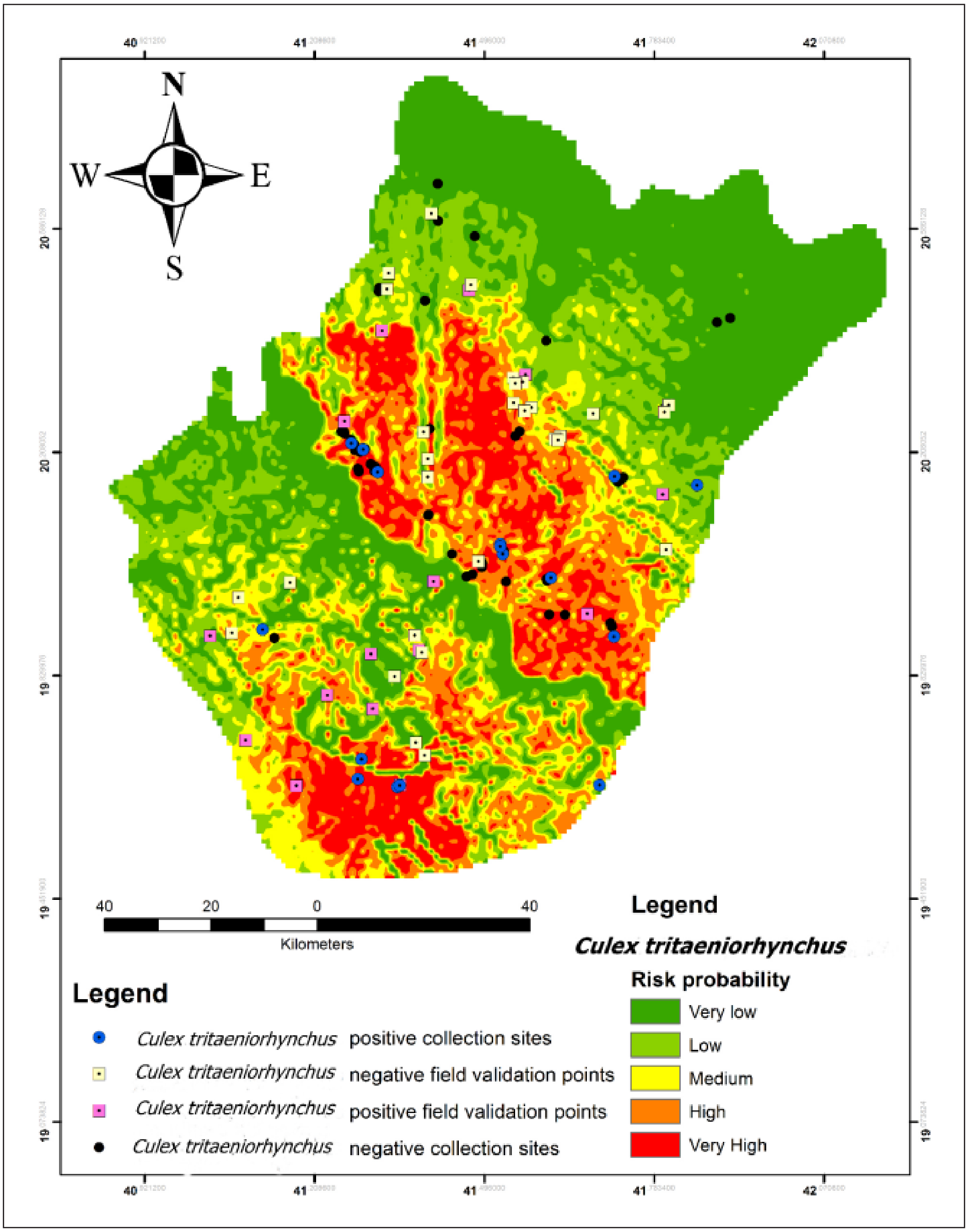

Figure 4. Risk probability distribution map for *Cx. tritaeniorhynchus* in Al-Bahah Province, Kingdom of Saudi Arabia

For *St. aegypti* risk distribution, there were 747.64 km^2 (6.23%) of the whole Al-Bahah Province at "very high", 1199.08 km^2 (9.99%) at "high", 1335.85 km^2 (11.13%) at "medium", 1430.67 km^2 (11.92%) at "low" and 7286.76 km^2 (60.72%) at "very low risk". The comparative distribution of risk areas in different districts of Al-Bahah Province is shown in Figure 5.

For *Cx. tritaeniorhynchus*, there were 1484.65 km^2 (12.37%) at "very high", 1700.83 km^2 (14.17%) at "high", 1808.47 km^2 (15.07%)

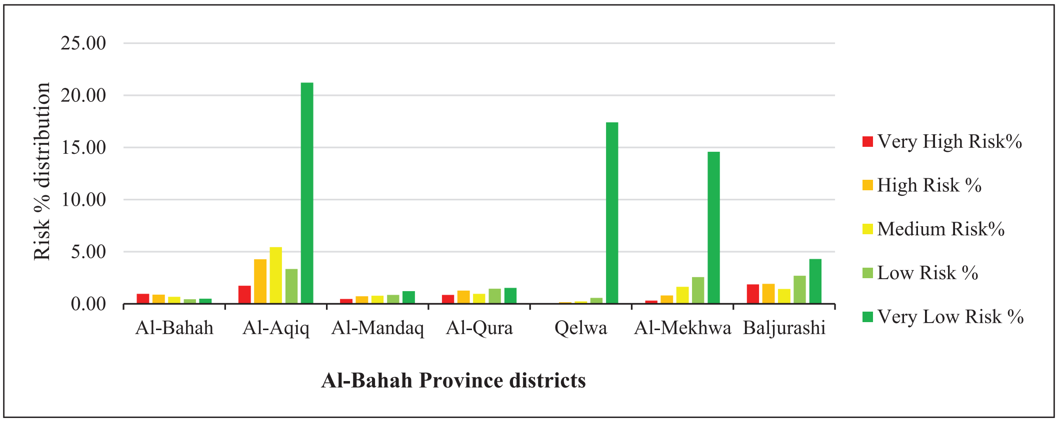

Figure 5. Risk probability distribution of *St. aegypti* in different districts of Al-Bahah Province, Kingdom of Saudi Arabia

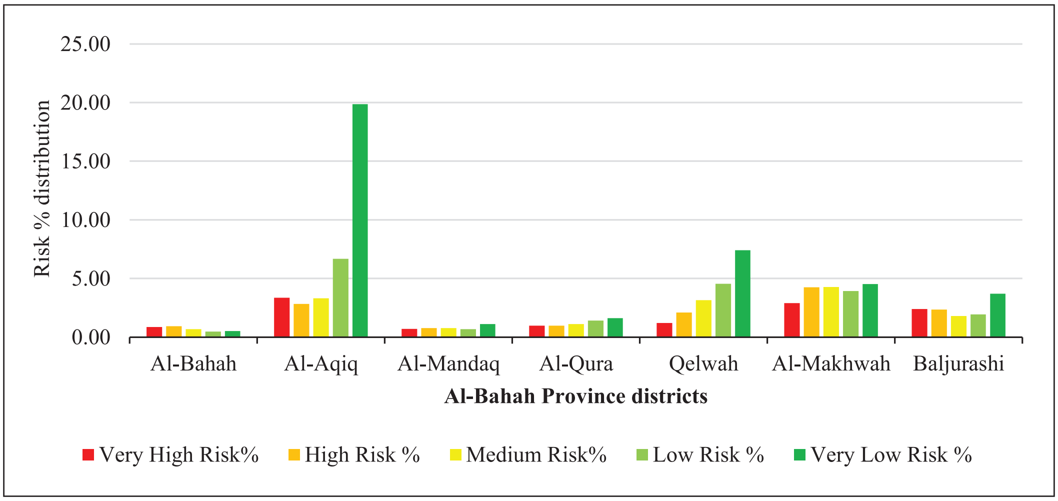

Figure 6. Risk probability distribution of *Cx. tritaeniorhynchus* in different districts of Al-Bahah Province, Kingdom of Saudi Araiba

at "medium", 2355.36 km^2 (19.63%) at "low" and 4650.70 km^2 (38.76%) at "very low" risk (Figure 6).

Field validation of the models

To validate the models in the field, all sites of Al-Bahah Province were visited according to risk classes using a hand held GPS (Tables 3 & 4). For *St. aegypti*, 5 sites were visited in "very high" risk areas and only 2 sites (40%) were positive. All the other "high", "medium", "low" and "very low" risk areas were negative (Table 3). Mostly the negative collection sites were at low elevation, but some at high elevation.

For *Cx. tritaeniorhynchus*, 41 sites were visited and four sites (67%) were found positive in "very high" risk area, four sites (44%) in "high", five sites (33%) in "medium", two sites (18%) in "low risk" probability areas. In "very low" risk areas, no larvae were detected (Table 4).

DISCUSSION

GIS/RS techniques are very helpful in creating predictive distribution maps of mosquito vectors and ultimately vector borne diseases (Kulkarni *et al.*, 2010; Abdel-Dayem *et al.*,

Table 3. Field validation for the ecological niche modeling of *St. aegypti*

Probability	Longitude ° E	Latitude ° N	Number of collected larvae
>0.6	41.653	19.983	10
	41.365	20.16	4
	41.3632	20.2442	0
	41.486	20.023	0
	41.67	19.934	0
0.4-0.6	41.333	20.36	0
	41.326	20.161	0
	41.464	20.119	0
	41.698	19.92	0
	41.587	20.006	0
	41.259	20.26	0
0.3-0.4	41.6206	20.2283	0
	41.7	20.094	0
	41.173	19.655	0
	41.266	19.882	0
	41.8033	20.0427	0
	41.5481	20.3241	0
0.1-0.3	41.406	20.168	0
	41.4004	20.1967	0
	41.6246	20.2349	0
	41.6159	20.23	0
	41.6794	20.2745	0
	41.8081	20.2874	0
	41.8006	20.2754	0
	41.7978	20.1364	0
	41.47	20.482	0
	41.5656	20.3394	0
	41.063	19.681	0
0.0-0.1	41.334	20.5113	0
	41.3782	19.8976	0
	41.3852	19.8727	0
	41.3901	19.8684	0
	41.3819	19.6996	0
	41.5756	20.2836	0
	41.566	20.2824	0
	41.5608	20.3265	0
	41.5545	20.3314	0
	41.0686	19.9016	0
	41.2303	19.7962	0
	41.0796	19.9617	0
	41.41	19.989	0

Table 4. Field validation for the ecological niche modeling of *Cx. tritaeniorhynchus*

Probability	Longitude ° E	Latitude ° N	Number of collected larvae
> 0.7	41.565576	20.33944	20
	41.67	19.934	9
	41.063	19.681	3
	41.259	20.26	5
	41.8081	20.2874	0
	41.5481	20.324128	0
0.5-0.7	41.47	20.482	1
	41.353457	19.64419	9
	41.046781	19.53612	24
	41.230346	19.796246	4
	41.406	20.612	0
	41.394915	19.694329	0
	41.068632	19.901575	0
	41.486	20.023	0
	41.079567	19.961662	0
0.3-0.5	41.797838	20.136402	5
	41.385192	19.872744	7
	41.304	19.866	2
	41.4	20.166	0
	41.68	20.273	0
	41.545	20.334	0
	41.031979	19.896857	12
	41.306955	19.773257	2
	41.624646	20.234883	0
	41.62064	20.228337	0
	41.800587	20.275416	0
	41.803347	20.04271	0
	41.378187	19.897571	0
	41.390055	19.868393	0
	41.575573	20.283641	0
0.2-0.30	41.32278	20.413695	1
	41.41	19.989	1
	41.333971	20.51125300	0
	41.344	19.828	0
	41.38	19.716	0
	41.167	19.987	0
	41.564	20.278	0
	41.393	20.242	0
	41.400425	20.196701	0
	41.615858	20.230046	0
	41.560805	20.326519	0
0.01-0.2		Inaccessible Places	

2012). These techniques are also very helpful in embarking large scale control projects on mosquito vectors. In Saudi Arabia, only distribution modeling of *Cx. tritaeniorhynchus* has been done in Jazan Province (Sallam *et al.*, 2013), but no work has been done for DF vectors in the other parts of the kingdom.

Significant correlation has been found between the abundance (% collected) of larvae and TDS. This result is consistent with the previous findings of Alahmed *et al.* (2009), Kheir *et al.* (2010) and Sallam *et al.* (2013), where low TDS values were found to provide suitable habitat for mosquito larvae presence. During field validation of these models, most of the mosquito larvae were found in those habitats where TDS breeding site water was low.

Our results showed that topographical variables (altitude, soil, slope, streams and aspect) contribute more in the modeling of *St. aegypti*. These findings are consistent with previous findings (Mweya *et al.*, 2013; Nmor *et al.*, 2013; McCann *et al.*, 2014).

Elevation provided the maximum contribution (38.1%) in terms of predicting *St. aegypti* occurrence. The highest probability was in the areas with elevation >1650 meters in Al-Sarah sector of the Province. This study agrees with the result of Lozano-Fuentes *et al.* (2012), where this species was found up to 2,130 meters. However, there are some findings which are different than our modeling i.e. temperature related variables represent a major constraint on the distribution of *St. aegypti* (Machado-Machado, 2012) and in our findings, mean temperature of driest quarter contributes only 1.4 % in the distribution of *St. aegypti*. Rogers *et al.* (2014) found that precipitation and temperature related variables are main contributor in the modeling. These findings may be due to the selection of the variables. In our study both topographical and bioclimatic variables have been used for the distribution.

Temperature and precipitation are two important climatic factors, which affect the distribution of mosquitoes (Lin and Lu, 1995; Murty *et al.*, 2010). The temperature relating variables (bio6, bio9, bio5) contribution was maximum (51.1%) in the modeling of *Cx. tritaeniorhynchus*. This result is consistent with the findings of Masuoka *et al.* (2010), in which they found that minimum temperature of July and land cover are the most important factors contributed in the modeling of this vector. However, this result is not consistent with the modeling in Jazan Province (Sallam *et al.*, 2013), where precipitation of the warmest quarter provided the maximum contribution in predicting *Cx. tritaeniorhynchus* occurrence.

There are some limitations in this study. For the field validations of these models, mosquito collection was not enough from the target sites. This is because of the topography of certain areas of the Province (Shereif *et al.*, 2014). Anyhow, to overcome this problem, the nearby "high risk" areas were searched out for the water and collection of mosquitoes. This was successful sometimes but not always, especially for the collection of *St. aegypti* as most of the places were not accessible. Because this species has close association with man (antrhopophilic) (Kemp & Jupp, 1991; Schultz, 1993), that is why this species prefers those highly populated areas. Collection of this species inside the homes becomes difficult in Al-Bahah where only two sites were positive in "high risk" areas and all the other 39 sites were negative due to absence of water or inaccessibility to those sites, although, our two positive sites in the "high risk" areas confirm our model prediction. The absence records during field validation for these vectors might be due to TDS values higher than 1 ppm and high temperature, because too high temperature becomes unfavorable for mosquito larvae (Craig *et al.*, 1999; Clements *et al.*, 2006).

In conclusion, the presence of these two important vectors constitutes a major health problem in Al-Bahah, and every effort should be made for their control. Further studies are required to study the temporal effect of climatic factors on the distribution and vectorial capacity of these two vectors.

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