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Habitat suitability modeling of mosquito species in Faiyum Governorate, Egypt, using GIS

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Abstract

Background The life cycle and geographic range of mosquitoes are profoundly influenced by weather conditions. In Faiyum Governorate, Egypt, researchers looked at over 42 different mosquito breeding areas in the wild. *Culex pipiens, Culex antennatus, Culex perexiguus, Culex theileri, Anopheles multicolor, Anopheles sergentii, Ochlerotatus caspius, Culiseta longiareolata,* and *Uranotaenia unguiculata,* were all represented among the collected mosquito larvae. Using Maxent, we identified the most important bioclimatic factors affecting habitat appropriateness for each species. In order to determine the link between a species' habitat appropriateness and bioclimatic factors, the computer builds response curves for each bioclimatic factor. All species risk maps, species richness maps, and individual species maps were generated with a Software that build interactive web maps (ArcGIS 10.3).

Results Each mosquito species' range was impacted by four bioclimatic factors. The most influential factors were those linked to temperature and precipitation. *Culex antennatus, Culex perexiguus, Culex pipiens,* and *Ochlerotatus caspius* responded best to temperature-related factors. Precipitation of wettest month (bio 13) was effective in four species (*Anopheles multicolor, Culex antennatus, Culex perexiguus,* and *Culex pipiens*).

Conclusion Areas in the north and west of El-Fayoum district (Zawyat El-Karadsah, Beni-Saleh, and Monshat Abd-Allah), in Tamiya in Kafr Mahfouz, in the south of Abshway, especially in Tobhar, in the north of Atssa, in the south and center of Sinnuris have been identified as high-risk areas and more susceptible to mosquito-borne diseases.

Keywords Habitat suitability, Mosquito, Modeling, GIS, Egypt

1 Background

Diseases spread by vectors kill more than 17 percent of the world's population every year, resulting in over 700,000 annual deaths [1]. Mosquitoes are carriers of a variety of parasites and viruses, including the Sindbis virus, which causes Ockelbo disease, chikungunya, dengue, Japanese encephalitis, malaria, lymphatic filariasis, dirofilariasis, West Nile virus, Zika virus, Usutu virus, Tahyna virus, Batai virus, and Japanese encephalitis [2–4]. Because they transmit deadly diseases to animals, mosquitoes threaten not only humans but also livestock. Equine alphaviruses, which can be lethal to horses, are spread by certain mosquito species [5]. Also, Japanese encephalitis virus (JEV) can infect dogs, cats, goats, buffaloes, chickens, and other domestic species [6]. There are five mosquito genera, Culex, Anopheles, Aedes, Culiseta, and Uranotaenia, which are the most prevalent genera in Egypt. Most species in these genera serve as significant disease vectors for both humans and animals [7, 8]. Throughout Egyptian territory, the fauna of mosquito species is very diverse, especially around the Nile

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Valley. Faiyum Governorate is located in western Egypt and is a significant agricultural region. The area's water resources, such as the Nile River and Lake Qarun, make it an ideal mosquito breeding site. Faiyum Governorate is home to a variety of mosquito species, including Anopheles mosquitoes, which are the primary vectors of malaria in this region, and they breed in stagnant water bodies, such as irrigation canals and rice paddies. Culex mosquitoes are known to transmit diseases, such as West Nile virus and filariasis [9–11]. They may be found in sewage, drainage ditches, and other water sources where they can reproduce. Malaria, dengue fever, and the Zika virus are just a few of the illnesses spread by the Aedes mosquito. They procreate in manmade objects like empty cans, flower vases, and tires [12–14]. These mosquitoes can spread a variety of diseases, making their presence in Faiyum Governorate a serious public health concern. In terms of malaria, Faiyum Governorate is a significant epicenter because the illness has been present there since antiquity. Polymerase chain reaction (PCR) assays were used to confirm its presence in Egyptian mummies (El-Fayoum) [15]. Anopheles mosquitoes are the most important vectors of malaria transmission in the area. Malaria is a serious public health concern in Egypt, and Faiyum Governorate is one of the regions with the highest incidence of the disease [16–18]. Several public health initiatives, such as the use of insecticide-treated bed nets, repellents, and larvicides to target mosquito breeding grounds, are used to lessen the effects of disease spread by mosquitoes. The absence of clear distribution maps of these mosquito species in the study area reduces the effectiveness of the control strategy. Such maps can easily be generated using data science. Many biologists are motivated to solve environmental problems using data science [19]. Biodiversity biological records are the focus of informatics, a subfield of data science. Information on biodiversity may benefit from bioinformatics methods for display, discovery, exploration, and analysis of biological data [20]. It relies on digitally preserved taxonomic, biogeographic, and ecological information gathered in the contemporary era [21]. Biodiversity informatics in the final set usually produces species distribution models (SDMs). SDMs calculate the relationship between species records at sites and species spatial analyses [22, 23]. It makes predictions on where species will be found and how communities and ecosystems will change as a result of climate and other environmental shifts [24]. Spatial biodiversity patterns may be broken down into their ecological and evolutionary components with the use of species distribution models [25]. SDMs have been used in a variety of disciplines, including ecology, parasitology, biogeography, conservation ecology, and evolution, to evaluate species' spatial distributions in recent years [26–30]. The maximum entropy model (Maxent) [31] is a crucial resource for modeling species distributions since it generates a jackknife, accommodates limited data, and provides reliable results [22, 31, 32]. Maxent is superior to other ecological niche models for forecasting species distribution when just a few sample places are provided [25, 33]. Replication is made easier since cross-validation and testing of the model's performance are made possible by repeated subsampling [34]. A Geographical Information System (GIS) is a database and set of related software applications that allows users to see and manage geographic data, conduct geographical analysis, and simulate real-world events [35, 36]. The application of this new technique in mosquito ecology will help in their control and evaluation of their status in different landscapes. The present study aimed to apply SDMs tools to monitor mosquito species and their suitable habitats in El Fayoum by surveying the governorate and assessing the status of these vectors in this important area of Egypt.

2 Methods

2.1 Occurrence data and study area

El-Fayoum is a 6,068.7 Square kilometers (km^2) agricultural governorate in Egypt located below sea level. (https://en.wikipedia.org/wiki/Faiyum_Governorate). It lies 90 km (km) southwest of Cairo and is connected to the Nile by the Bahr Youssef River, which enters the governorate from the east and branches into other rivers before emptying into Qaroun Lake. The Governorate, which resembles a depression, is situated in the western desert between the latitudes of 29° 02' and 29° 35' N and the longitudes of 30° 23' and 31° 05' E. Sinnuris, Tamiya, El-Fayoum, Atssa, Abshway, and Youssef El-Sedik are the six districts that make up this city. El-Fayoum has a hot, dry climate with infrequent winter rain and abundant sun throughout the year. In El-Fayoum, it is estimated that there are 3845.1 h of sunshine every year. In January, the average temperature is 13.5 Degree Celsius (°C), while in August, it is 30.6 °C. According to climate-data.org (https://en.climate-data.org/africa/egypt/faiyum-Governorate/faiyum-5569/#weather), May had the lowest relative humidity (31.46%) and December had the highest (55.31%). In October and November 2020, mosquito larvae were collected from locations where they might develop successfully throughout the governorate, as shown in Fig. 1. The 42 sites that made up the breeding habitats were canals, sewage tanks, agricultural puddles, stagnant water puddles, and wetlands. According to the World Health Organization (WHO)[37], The dipping technique was used to capture the larvae, and further laboratory identification followed Mattingly and Knight criteria [38], Harbach [39], Harbach [40], Savage and Strickman [41], Harbach [42], and Harbach [43] (Fig. 1).

Fig. 1 Mosquito breeding sites at Fayoum governorate, Egypt

Table 1 Environmental parameters that were used to predict the current habitat suitability distribution of mosquito species

Variables	Description
Bio 1	Annual mean temperature
Bio 2	Mean diurnal range (mean of monthly max temp – min temp)
Bio 3	Isothermality (bio2 / bio7) × 100
Bio 4	Temperature seasonality (standard deviation × 100)
Bio 5	Max temperature of warmest month
Bio 6	Min temperature of coldest month
Bio 7	Temperature annual range
Bio 8	Mean temperature of wettest quarter
Bio 9	Mean temperature of driest quarter
Bio 10	Mean temperature of warmest quarter
Bio 11	Mean temperature of coldest quarter
Bio 12	Annual precipitation
Bio 13	Precipitation of wettest month
Bio 14	Precipitation of driest month
Bio 15	Precipitation seasonality (coefficient of variation)
Bio 16	Precipitation of wettest quarter
Bio 17	Precipitation of driest quarter
Bio 18	Precipitation of warmest quarter
Bio 19	Precipitation of coldest quarter

3 Climatological data

Climate data with a spatial resolution of 30 arc seconds were downloaded from the WorldClim database (http://www.worldclim.org/) (1 km). The present-day weather was calculated using data from 19 different meteorological elements in this investigation (Table 1). We started by utilizing Maxent's jackknifing function to estimate the minimum set of variables necessary for our purposes. Jackknife parameters with zero impact on species distribution were also discovered in this study. Strongly linked parameters with little biological impact on the species were eliminated using the Universal tool in ArcGIS 10.3 SDM Tools (Remove highly correlated variables) [44]. Therefore, we chose four important factors for each species to consider while establishing a suitable habitat in the study area. ArcGIS V.10.3 was used to clip and resize all bioclimatic layers to fit inside the boundaries of the Faiyum governorate, and the resulting ASCII grid files were imported into Maxent. Extract by mask in Arc Map was used to collect data for each bioclimatic variable [45]. These factors were included in models of species dispersion [46, 47].

4 Habitat suitability modeling

In this study, we used the maximum entropy model (Maxent version 3.3.3 k, available at http://www.cs.princeton.edu/wschapire/maxent/) since it performed better than other modeling techniques when dealing with limited data sets (see reference [48]). To determine the correlations between a species' habitat appropriateness and bioclimatic parameters, the software assigns a value between 0 and 1 to each bioclimatic variable and creates response curves for each [49]. Maxent will automatically delete any entries that are entered twice in the same cell. To train our models, we used 75% of the occurrence data, whereas 25% were used for testing [50]. By running the model 10 times for each species and averaging the results, tenfold cross-validation was used to increase model performance. The area under the curve (AUC) of the receiver operating characteristics (ROC) was used to evaluate the performance of the models [51, 52]. The AUC may be anywhere from 0 (random discrimination) to 1 (perfect discrimination).

5 Species richness and risk map

The species richness map was obtained by submitting the presence/absence maps that were generated for each of the five mosquito species using ArcGIS 10.3. This process was performed using the Arc toolbox Map algebra. All recorded data of collected mosquito species (either the five selected species or the remaining species that were not included in the modeling study) were implemented in Maxent software using the 19 bioclimatic variables to produce a risk map that represents the most suitable area for all mosquitoes reported in the governorate [53].

6 Results

6.1 Model performance contribution of bioclimatic variables

With AUCs between 0.77 and 0.94, the models for all five mosquito species outperformed chance. These results indicate the perfection of the model for the five species: *Anopheles multicolor* (Cambouliu, 1902) 0.83; *Culex antennatus* (Becker, 1903) 0.94; *Culex perexiguus* (Theobald, 1901) 0.89; *Culex pipiens* (Linnaeus, 1758) 0.82; and *Ochlerotatus caspius* (Pallas, 1771) 0.77, where any results above 0.75 consider acceptable for the generated models. Species' distributions are profoundly impacted by changes in both temperature and precipitation. Insect species such as *Culex antennatus, Culex perexiguus, Culex pipiens,* and *Ochlerotatus caspius* were best predicted by factors associated with temperature. Four species benefited from the heavy rains that fell in the wettest month (bio 13) (*Anopheles multicolor, Culex antennatus, Culex perexiguus, and Culex pipiens*). The effect of each bioclimatic variable used in the generation of the models was tabulated using the jackknife test (Table 2 and Fig. 2). The response curves for the most effective climatological parameters contributing to the distribution of each species are shown in Fig. 3. The curves show how the occurrence of each species is correlated with each variable. Table 2 shows percentages of bioclimatic variables used in modeling mosquito distribution throughout Faiyum Governorate.

By reading Fig. 2a, it showed that bio 9 (Mean Temperature of Driest Quarter) is the best parameter for *Culex antennatus*. Bio 16 (Wettest Quarter Precipitation) and bio 13 (Wettest Month Precipitation) tied for second and third place in terms of impact, respectively, while bio 7 (Annual Temperature Range) ranked last.

Biotype 9 (Mean Temperature of Driest Quarter), Biotype 12 (Annual Precipitation), and Biotype 13 (Day length) were the most important environmental factors for *Culex perexiguus* (Fig. 2b) (Precipitation of Wettest

Table 2 Percentages of bioclimatic variables used in modeling mosquito distribution throughout Faiyum Governorate

Sp.	Bioclimatic variable	Description	Contribution %
Cx. antennatus	Bio 7	Temperature annual range	9.6
	Bio 9	Mean temperature of driest quarter	65
	Bio13	Precipitation of wettest month	9
	Bio 16	Precipitation of wettest quarter	16.4
Cx. perexiguus	Bio 2	Mean diurnal range	16.6
	Bio 9	Mean temperature of driest quarter	59.2
	Bio 12	Annual precipitation	5.5
	Bio 13	Precipitation of wettest month	18.8
Cx. pipiens	Bio 3	Isothermality	57.8
	Bio 5	Max. temperature of warmest month	23.8
	Bio 12	Annual precipitation	10.6
	Bio 13	Precipitation of wettest month	7.8
An. multicolor	Bio 5	Max. temperature of warmest month	9.3
	Bio 10	Mean temperature of warmest quarter	10
	Bio13	Precipitation of wettest month	79.5
	Bio 16	Precipitation of wettest quarter	1.6
Oc. caspius	Bio 3	Isothermality	18.3
	Bio 5	Max. temperature of warmest month	51.9
	Bio 9	Mean temperature of driest quarter	18
	Bio 12	Annual precipitation	11.8

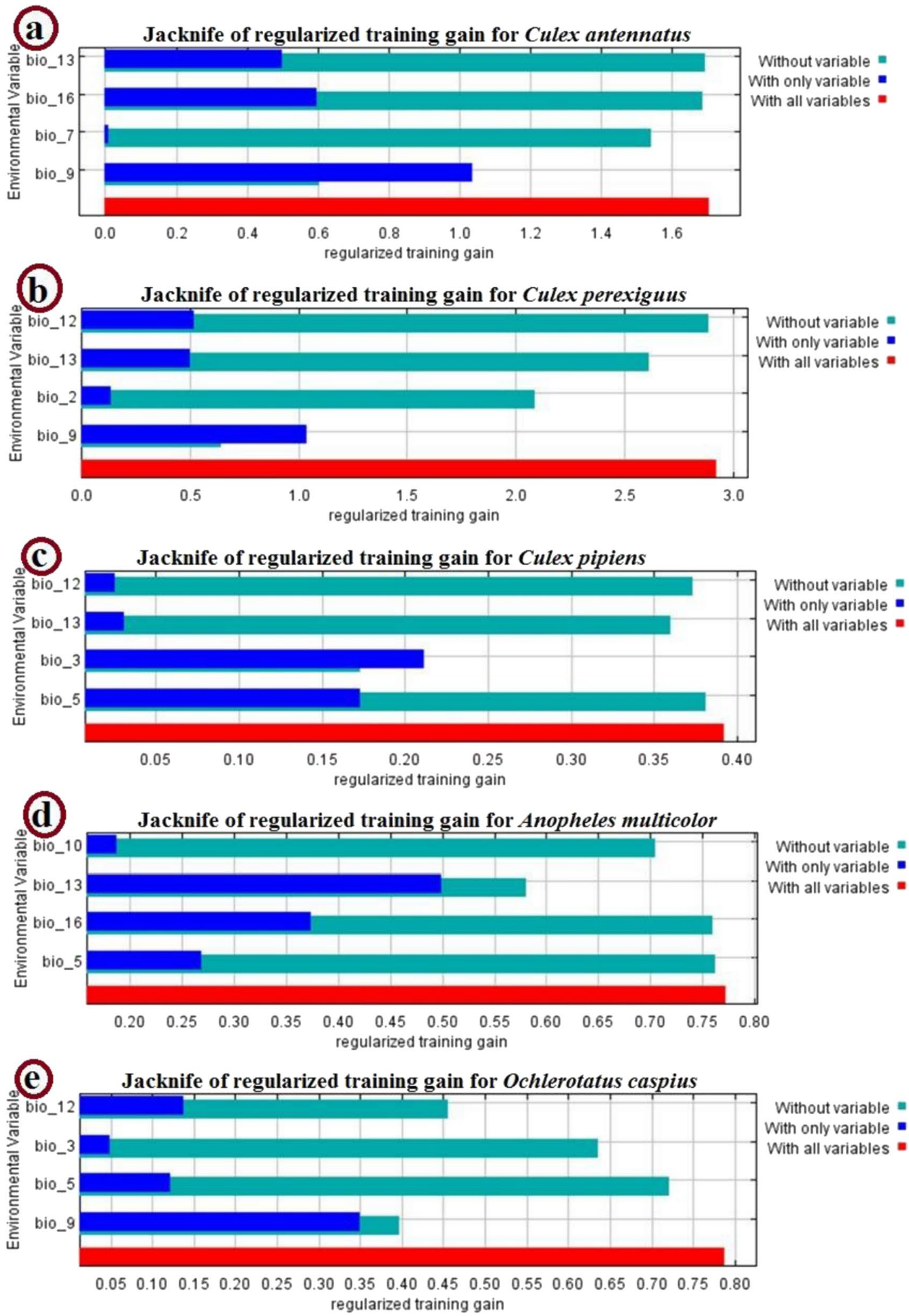

Fig. 2 Jackknife test of the most effective bioclimatic variables contributing to the distribution model of the five mosquito species throughout Faiyum Governorate. Bio 2: Mean Diurnal Range, bio 3: Isothermality, bio 5: Max Temperature of Warmest Month, bio 7: Temperature Annual Range, bio 9: Mean Temperature of Driest Quarter, bio 10: Mean Temperature of Warmest Quarter, bio 12: Annual Precipitation, bio 13: Precipitation of Wettest Month, bio 16: Precipitation of Wettest Quarter

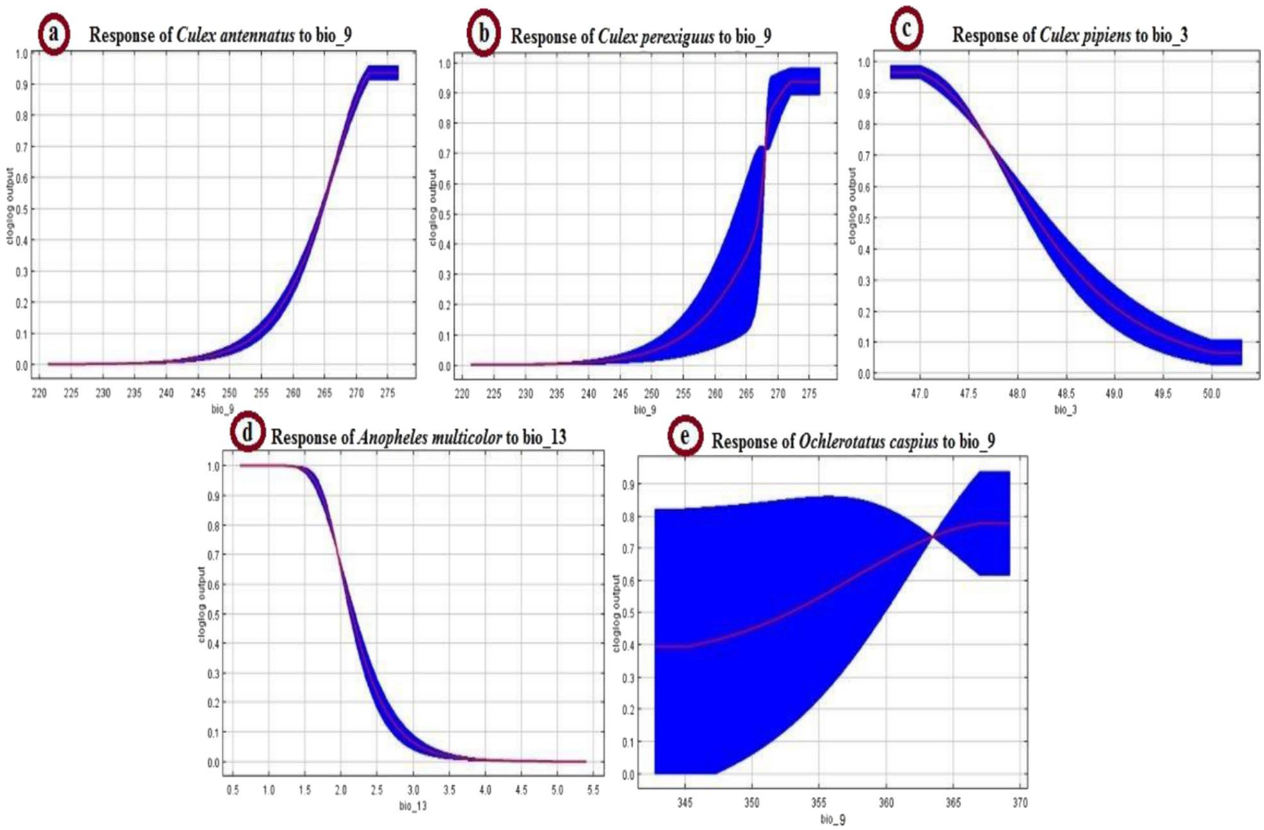

Fig. 3 The response curve of the most effective bioclimatic variables in the distribution of **a** *Culex antennatus*, **b** *Culex perexiguus*, **c** *Culex pipiens*, **d** *Anopheles multicolor*, **e** *Ochlerotatus caspius*

Month). The least productive biovariable in this study was bio 2 (Mean Diurnal Range).

In the case of *Culex pipiens* (Fig. 2c), bio 3 (isothermality) had the greatest impact, followed by bio 5. (Max Temperature of Warmest Month). These two factors explain 81.6% of the variation. Among the most useful metrics, bio 12 was the least useful, while bio 13 (Wet Month Precipitation) ranked third (Annual Precipitation).

Bio 13 (Precipitation of Wettest Month) and bio 16 (Day length of Day) were the two most useful parameters in controlling *Anopheles multicolor* (Fig. 2d) (Precipitation of Wettest Quarter). In addition, this species ranked third for bio 5 (Highest Temperature in Hottest Month) and fourth for bio 10 (Warmest Quarterly Average Temperature).

Figure 2 e shows that the most influential climatic factor for *Ochlerotatus caspius* was the mean temperature of the driest quarter (bio 9), followed by annual precipitation (bio 12), the maximum temperature of the hottest month (bio 5), and the minimum temperature of the coldest month (bio 3) (isothermal).

7 Mosquito species distribution modeling

The collected mosquito larvae were morphologically identified in the laboratory according to Mattingly and Knight (38), Harbach (39), Harbach (40), Savage and Strickman (41), and Harbach (42), Harbach (43) into nine mosquito species: *Culex pipiens*, *Culex antennatus*, *Culex perexiguus*, *Culex theileri* (Theobald, 1903), (Fig. 4), *Anopheles multicolor*, *Anopheles sergentii* (Theobald, 1907) (Fig. 5), *Ochlerotatus caspius*, *Culiseta longiareolata* (Macquart, 1838), and *Uranotaenia unguiculata* (Edwards, 1913) (Fig. 6). Five mosquito species were the most frequent: *Culex antennatus, Culex perexiguus, Culex pipiens, Anopheles multicolor,* and *Ochlerotatus caspius.* Of these five species, *Culex pipiens* was the most abundant.

8 Habitat suitability modeling

According to the acquired results of the selected species distribution modeling, their distribution patterns were similar to their real situation throughout the governorate (Fig. 7).

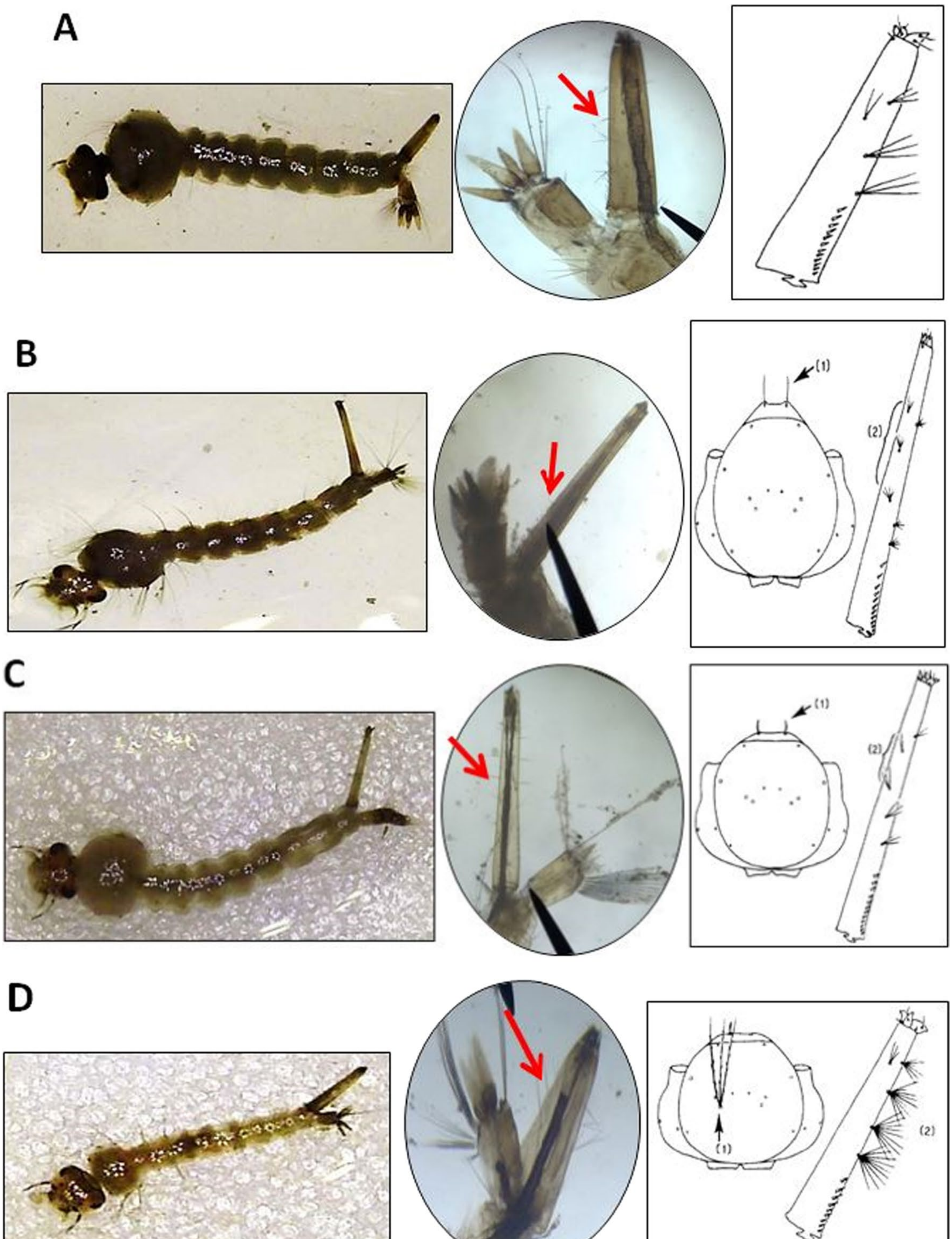

Fig. 4 Morphologically identified mosquito larvae in Faiyum Governorate: **A** *Culex pipiens*, **B** *Culex antennatus,* **C** *Culex perexiguus,* **D** *Culex theileri*

Fig. 5 Morphologically identified mosquito larvae in Faiyum Governorate: **A** *Anopheles sergentii* **B** *Anopheles multicolor*

For *Culex antennatus*, the most current suitable habitats appeared in Atssa (Abo Gandeer, Garado, Menia El-Heet) and El-Fayoum (the center of the city, Manashi El-Khatib, Belal Bin Rabah) districts, while in Tamyia (Kafr Mahfouz, Dar El-Salam, Sersena), Sinnuris (the center of the city, Fedmeen, Tersa, Behmo), and Abshway (Senaro, El-Agmeen) districts habitats were less suitable.

For *Culex perexiguus*, the highest suitability marked in El-Fayoum, Tamyia (Dar El-Salam, Sersena) and Atssa (Garado) districts, while medium to low suitable habitats showed in Sinnuris (Sanhor, Monshaat Tantawy), Abshway, and Youssef El-Sedik districts.

For *Culex pipiens*, the Abshway district displayed the highest suitability, followed by Sinnuris (Fedmeen) and Youssef El-Sedik (Kahk, El-Nazlah). Also, the habitat around Wadi El-Rayan protected area, El-Fayoum (Beni-Saleh, Manashi El-Khatib, Belal Bin Rabah) and Atssa (Abo Gandeer, Garado) districts showed high suitability while medium to low suitableness marked in Youssef El-Sedik, Sinnuris (Kafr Fazara, Abheet, El-Zaweia El-Khadra), Tamiya (Kafr Mahfouz, Kasr Rashwan, Fanos), El-Fayoum (El-Nasria, Ellahon, Hawart Elmaktaa), Atssa (Tatoon, Kalmshah) districts.

For *Anopheles multicolor*, the most suitable habitats marked in Atssa (Menia El-Heet, Abo Gandeer, Garado), Youssef El-Sedik (El-Nazlah), El-Fayoum (Zaweit El-Karadsah, Beni-Saleh), Tamiya (Dar El-Salam, Sersena, El-Rawdah), Sinnuris (Behmo, Garrfs, Motrtars), Abshway (Abo-Gnash, Tobhar, El-Agmeen, Senro), and around Wadi El-Rayan protected area. Additionally, medium suitability was noticeable in El-Fayoum (the center of the city, Monsheiat Abd-Allah) and Atssa (Tatoon) districts. Habitats showed low suitability for Qarun Lake.

For *Ochlerotatus caspius*, habitat suitability was the highest around Qarun Lake, in Sinnuris, Abshway, Tamiya (Kafr Mahouz), El-Fayoum (Beni-Saleh, Belal Bin Rabah), Atssa (Garado, Abo Gandeer), Youssef El-Sedik (Kahk, El-Shawashna, El-Nazlah), and around Wadi El-Rayan protected area. Medium habitat suitability marked in Tamiya (Fanos, Monshaiet El-Gammal, El-Rawda), El-Fayoum (El-Nasria, Ellahon, Hawart Elmaktaa), south of Atssa (Taton, Kalmshah), and Youssef El-Sedik. Sites with low suitability appeared at the marginal sites around the governorate.

9 Species richness and risk map

Five mosquito species were unequally distributed across the six administrative districts of the governorate (Fig. 8). *Culex antennatus* was noticeable in Tamiya (Kafr Mahfouz), east of El- Fayoum (El-Nasriah), center of Sinnuris, south of Atssa (Tatoun), north of Youssef El-Sedik (Kahk), and peripheral sites around Qarun lake. *Culex antennatus* and *Culex perexiguus* marked in the center of El-Fayoum, Sinnuris (Sanhour), Abshway (Aboksaah), Youssef El-Sedik (El-Shawashna), Atssa (Menya Elhiet).

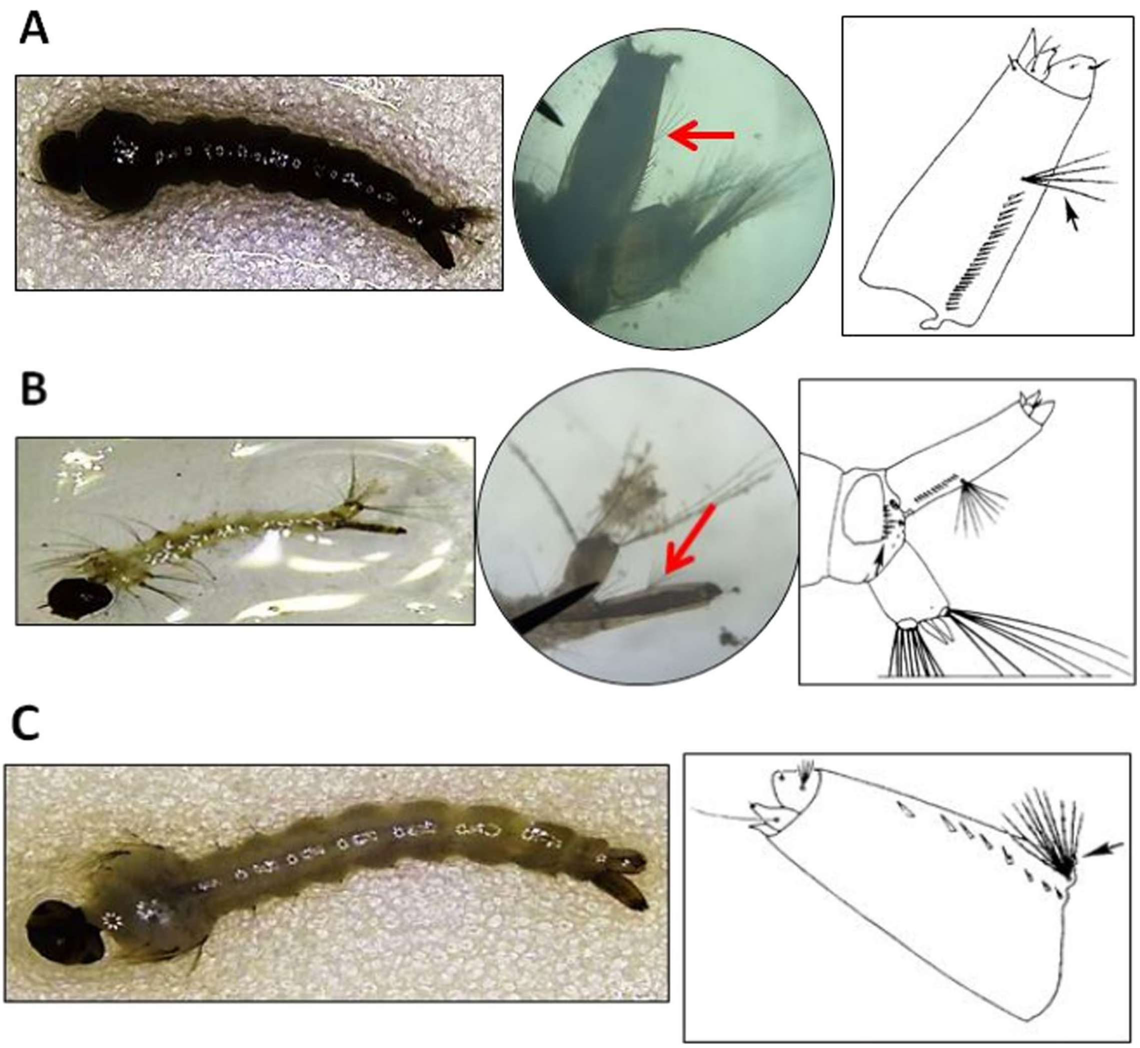

Fig. 6 Morphologically identified mosquito larvae in Faiyum Governorate: **A** *Ochlerotatus caspius,* **B** *Uranotaenia unguiculata* and **C** *Culiseta longiareolata*

Culex antennatus, Culex perexiguus, and *Culex pipiens* were abundant in the center of Atssa district, Youssef El-Sedik district (El-Nazlah, El-Hamoly), and around the Wadi El-Rayan protected area. *Culex antennatus, Culex perexiguus, Culex pipiens* and *Anopheles multicolor* were noticeable in Tamiya (Dar El-Salam), El-Fayoum (Zaweit El-Karadsah, Beni-Saleh), Sinnuris (Behmo), Abshway (Tobhar, Abo-Gnash), Atssa (Garado). *Culex antennatus, Culex perexiguus, Culex pipiens, Anopheles multicolor,* and *Ochlerotatus caspius* distributed in few sites in Sinnuris (Tersa, Ebheet, Nakalefa), El-Fayoum (Manashi El-Khatib, Belal Bin Rabah), and Atssa (Abo Gandeer) districts.

All recorded mosquito species were used to produce the risk map throughout the governorate (Fig. 9). El-Fayoum district north and west (Zawyat El-Karadsah, Beni-Saleh, and Monshat Abd-Allah), Kafr Mahfouz's Tamiya, Abshway south (particularly Tobhar), Atssa north, and the south and center of Sinnuris are all sites with extremely high danger markings (Kafr Fazara, Tersa, and Elzaweia El khadra). Additionally, high-risk places located in Atssa (Abu-Seer and El-Sawafna), Youssef El-Sedik especially in El-Nazlah and Sinnuris district (Behmo). Other places were vulnerable to medium mosquito risk, such as Bandar El-Fayoum, the center of Abshway, and Atssa (Definno) districts.

10 Discussion

The governorate of El-Fayoum is geographically distinct. It is distinguished by its gentle inclination and proximity to sea level. In addition, most people are employed in agriculture and related industries [54]. The mild environment and high relative humidity [55] that favor mosquito breeding in this region causes the season of disease

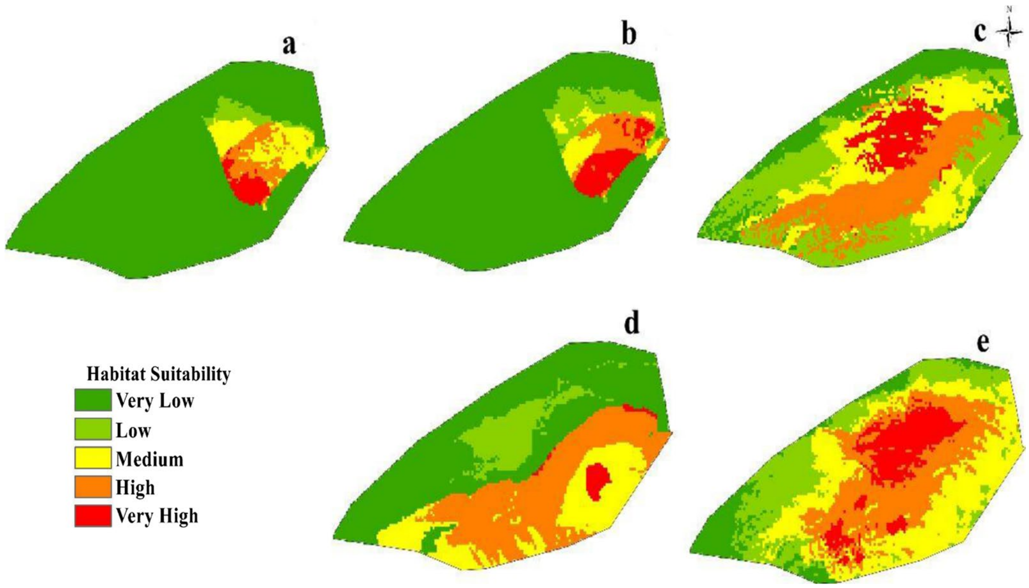

Fig. 7 suitability for: **a** *Culex antennatus,* **b** *Culex perexiguus,* **c** *Culex pipiens,* **d** *Anopheles multicolor, and* **e** *Ochlerotatus caspius.* The map here shows the presence of suitable habitat for each species where the red color represents the confirmation of present of each species through Fayoum territory, while the green indicates the complete absence of the species

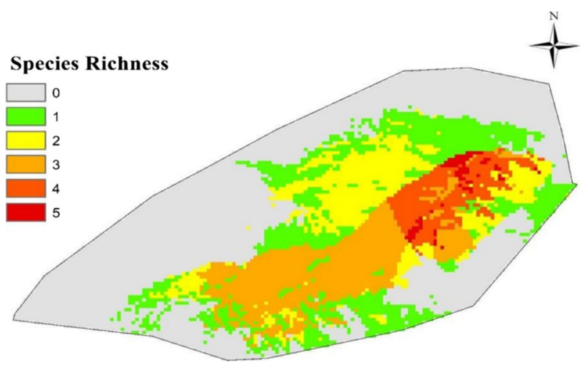

Fig. 8 Species richness of the most frequent mosquito types including; 1*: Culex antennatus,* 2: *Culex antennatus and Culex perexiguus,* 3: *Culex antennatus, Culex perexiguus and Culex pipiens,* 4: *Culex antennatus, Culex perexiguus, Culex pipiens and Anopheles multicolor,* 5: *Culex antennatus, Culex perexiguus, Culex pipiens, Anopheles multicolor* and *Ochlerotatus caspius.* The map shows the area of co-occurrence of the species through Fayoum territory

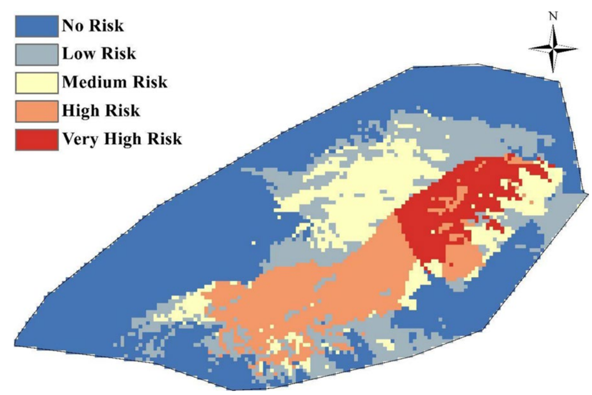

Fig. 9 Risk map for mosquito distribution throughout Faiyum Governorate. It is the most important as it represents the most important area that should be target of control when any outbreak of mosquitoes borne diseases through Fayoum territory

transmission to be extended to eight months each year, from roughly the end of March to the end of November [56].

Culex pipiens, Culex antennatus, Culex theileri, Culex perexiguus, Anopheles multicolor, Anopheles sergentii, Ochlerotatus caspius, Culiseta longiareolata, and *Uranotaenia unguiculata* were among the mosquito species discovered in this study. The five genera to which these species belong are Aedes, Anopheles, Culex, Culiseta, and Uranotaenia. These are the most prevalent genera in Egypt, according to numerous research [17, 40, 56, 57]. Most of these diseases are also important disease vectors for both humans and animals. Consider the genus Culex, which includes species such as *Culex pipiens*, which is thought to be the vector of numerous arboviruses, including the West Nile virus. Louis encephalitis, rift valley disease, and Sindbis viruses pose hazards to human life [58]. Wuchereria bancrofti, a filarial nematode that causes lymphatic filariasis, is transmitted by Cx. pipiens [59, 60]. According to Salamah et al. [61], the primary vector of lymphatic filariasis in Egypt is female *Cx. pipiens*. It can act as a hepatitis C virus (HCV) vector because an experimental study by El-Kholy et al. [62] demonstrated that *Cx. pipiens* can contract the disease, the virus reproduces inside the insect body, and the infected insect bites humans.

The current predicted habitat suitability modeling for *Culex pipiens* was high in many regions, especially in the Abshway and Sinnuris districts, which is consistent with the results of larval collection, as these districts recorded a high abundance of *Cx. pipiens* larvae. This species was the most frequent type and was found in different breeding habitats, especially in agricultural canals [61, 63]. Moreover, *Cx. pipiens* tolerated high degrees of pollution, as it was found with high densities in stagnant water habitats consistent with the findings of Ibrahim et al. [64] (particularly those related to human activities). Generally, breeding sites with the highest larval density were closest to houses, which agrees with Madewell et al. [65], who stated that there was an inverse relationship between the distance to the nearest house and larval abundance. Adult female mosquitoes require a blood meal for oviposition. It may be fed on mammalian blood meal especially human [66] or mixed blood meal [67]. In this context, the female preferred to stay close to its host for blood feeding and then chose the nearest breeding site for oviposition; therefore, breeding sites that were close to humans and animals were characterized by high larval density.

Ochlerotatus caspius was predicted to be high in many regions, such as Qarun Lake, Tamiya, El-Fayoum (Beni-Saleh), and areas with high seepage and sewage water [64, 68]. On the other hand, *Cx. antennatus* showed high suitability in Atssa, in agreement with the collected samples, as this district had the highest larval density of this species. Oringanje et al. [69] found that polluted breeding habitats encouraged the spreading of more Culicine species but Anopheline species did not prefer this type of habitats. This agrees with our results, as the majority of Culicine breeding sites were polluted. *Anopheles sergentii* larvae were found at two sites characterized by shallow, clean, freshwater, but some Anopheles multicolor breeding sites were polluted, similar to the observations of El-Hefniet al. [56].

Mosquito species were unequally distributed throughout the governorate. Sites displaying mosquito richness are vulnerable to disease transmission El-Hefni et al. [57]. The risk map shows that the desert part of the governorate displays no risk. On the other hand, highly populated agricultural areas display a very high risk of diversity and variety in breeding sites.

For bioclimatic variables, precipitation-related variables and temperature-related variables had the highest effects on all species distributions. High summer temperatures likely have a role in the distribution of the three species evaluated (*Culex antennatus, Culex perexiguus, and Ochlerotatus caspius*), as shown by the driest quarter mean temperature (bio 9). Temperature plays an important role in mosquito development and density because it is a cooled-blooded animal. Development is accelerated by increasing temperature until a definite limit is reached, mortality begins to increase, and the appropriate temperature for development is approximately 25–27 °C [70]. In addition, Loetti et al. [71] found that temperature between 7 and 25 °C had an inverse relationship with the time needed for larval development. According to research conducted by Mamai et al. [72], when temperatures were elevated to 27 °C, the number of larvae rose but the size of the emerging adult dropped. This, in turn, demonstrates how climate change has affected the distribution of different species [24].

Mosquito-borne diseases are a significant public health concern throughout Faiyum Governorate and Egypt as a whole. It is imperative that measures be taken to reduce mosquito populations and stop disease spreading for the sake of public health and safety.

11 Conclusion

This study is a baby step toward a fuller understanding of the ecology of significant mosquito species in Egypt. Further surveillance is needed to better evaluate the entire mosquito fauna in the region. In addition, the investigation of GIS and its modeling tools to predict the pattern of such distribution and abundance under different climate change scenarios is required.

Abbreviations

ArcGIS	Software that build interactive web maps
AUC	Area under the curve
°C	Celsius, the most common temperature scale in the world
GIS	Geographic Information System
HCV	Hepatitis C Virus
JEV	Japanese encephalitis virus
Km	Kilometer
PCR	Polymerase chain reaction
ROC	Receiver operating characteristics
SDMs	Species distribution models
WHO	World Health Organization

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Adel. Abdel Hakeem Abo El-Ela and Azza Mostafa supervised and followed up the practical work and revised the manuscript, Eman Ali Ahmed carried out the practical work and wrote the manuscript, Mohamed Gamal ElDin Nasser and Sara Ahmed Al-Ashaal analyzed results, modeling analysis, and manuscript writing, and Abdelwahab Khalil designed the experiments, review the manuscript, and final editing.

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Availability of data and materials
The datasets (tables and figures) generated and analyzed during the current study are available from the corresponding author upon reasonable request. All data generated or analyzed during this study are included in the present

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Declarations

Ethical approval and consent to participate
Not applicable.

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