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# Mosquito Habitat and Dengue Risk Potential in Hawaii: A Conceptual Framework and GIS Application\*

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Dengue is an emerging disease, and the distribution of the mosquito vector is partially mediated by environmental conditions. In this article, a new conceptual model is suggested that emphasizes the importance of including environmental variability in mosquito modeling studies. In an applied sense, mosquito habitat maps are developed for Hawaii using a GIS overlay of mosquito survival thresholds of temperature, precipitation, and stream/wetland location. Populated areas represent locations with the potential for an outbreak. The maps are adjustable based on expert knowledge input, and efforts to prevent or control outbreaks can be concentrated in those zones delineated by this study. **Key Words:** dengue, Hawaii, infectious disease, medical geography, mosquito-borne disease.

Dengue, spread through the bite of several species of the *Aedes* mosquito, is considered to be the world's most important mosquito-borne viral disease in terms of the number of infections and the number of people in the endemic region (National Research Council 2001). The World Health Organization estimates that there are approximately fifty million dengue infections each year, and about 2.5 billion people live in the region in which dengue is endemic (World Health Organization 2002). Following World War II, the disease has become a significant problem in developing countries, having spread globally since the end of an eradication program in the 1970s that was designed to eliminate the mosquito vector. The distribution of the *Aedes* mosquito has now spread beyond the area inhabited prior to the start of the program, and dengue is now present in much of the tropics and subtropics, including areas along Mexico's border with the United States (Centers for Disease Control and Prevention 2005).

The focus of this study is the 2001–2002 dengue outbreak in Hawaii, spread by the *Aedes albopictus* mosquito (Clark et al. 2002; Gratz 2004; Effler et al. 2005). The islands had previously been free of dengue since the 1940s

(Gilbertson 1945; Wilbar 1947; Effler et al. 2005), and this outbreak is illustrative of the role dengue is playing on a global scale as an emerging infectious disease. The goals of this article are twofold: to develop an improved conceptual framework for studying mosquito-borne diseases that includes ideas of spatial and temporal variability, and to employ environmental variability notions in an examination of mosquito habitat and dengue in Hawaii that can aid in public health decision-support.

Specifically, this research seeks to answer the following questions:

- What are the fine-scale spatial relationships between *Ae. albopictus* and climate variability?
- How do human and physical landscape features interact in Hawaii to create potential dengue habitat?

These questions are answered through an examination of the broad factors that contribute to the creation of mosquito habitat and potential dengue areas using a geographic information system (GIS), and the development of adjustable (based on user input) mosquito habitat and dengue potential maps for Hawaii for use in

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decision-support. The study is approached from a disease ecology perspective, and is also placed in the context of emerging diseases. Disease ecology seeks to understand the ways in which inorganic, organic, and sociocultural stimuli interact to produce disease (Meade and Earickson 2000). Emerging diseases refer to infections that have recently appeared or are experiencing an increase in number of cases or increase in range, or both (Morse 1995). The emergence of a particular disease can be related to any or all of the following factors: microbial changes; social, political, and economic factors; ecological factors; and physical environmental changes (Smolinski, Hamburg, and Lederberg 2003), thus linking the concept of emerging diseases to disease ecology. This study illustrates that the dengue outbreak in Hawaii serves as an example of dengue's emergence given the global spread of both the mosquito vector and the disease agent.

## Dengue Background

Several *Aedes* species are capable of transmitting dengue, but the principal vector is *Ae. aegypti*, with *Ae. albopictus* and others playing a lesser role on the global level. Although *Ae. aegypti* is responsible for more cases of dengue around the world, *Ae. albopictus* is the focus of this study given that it was implicated in the Hawaiian outbreak. *Ae. albopictus* was also responsible for outbreaks in Japan in 1942 to 1944 and in the Seychelles in 1976 and 1977 (Gratz 2004). It is believed that *Ae. albopictus* evolved in rural regions of tropical Southeast Asia and, through human migration, made its way to villages and cities where it became peri-domesticated (Gubler 1997). Hawaii remained free of mosquitoes until the *Culex* mosquito was transported aboard a ship from Mexico in 1826, and *Ae. albopictus* was widespread by 1902 when Hawaii's species were catalogued (Usinger 1944; Effler et al. 2005). In recent years, it is thought that *Ae. albopictus* has spread around the world through the trade of used tires; it was likely introduced into North America in the 1970s or early 1980s (Reiter and Darsie 1984; Sprenger and Wuithiranyagool 1986; Hawley et al. 1987; Craven et al. 1988; Moore and Mitchell 1997). The movement of goods (used tires, specifically) is important for the introduction of the mosquito to

new locations, and the movement of humans transfers the virus from place to place.

For a dengue outbreak to occur, three factors must be present. First, a population of *Aedes* mosquito must be established. Second, the virus must be introduced to the area by an infected person. Finally, there must be a human population susceptible to the particular dengue serotype (i.e., strain) that is brought into the area. For example, if most people have already been infected with a specific serotype and that serotype is reintroduced, an outbreak will not occur. Therefore, in a nonendemic region such as Hawaii, once mosquitoes are established, an epidemic may occur when the dengue virus is introduced, such as through a traveler returning from an endemic region. The epidemic cycle is initiated when a local *Aedes* mosquito bites an infected person and itself becomes infected, and the cycle is maintained when the newly infected mosquito bites a susceptible person, transferring the virus.

Following a human infection, symptoms may appear after an incubation period of several days. Symptoms include fever, severe headache, joint and back pain, and nausea; those experiencing the more severe hemorrhagic form of the disease (dengue hemorrhagic fever, or DHF) can suffer from all of the preceding symptoms as well as skin and internal hemorrhaging (Halstead 1997). Although hemorrhaging is most typically associated with DHF, it is not uncommon for some form of hemorrhaging to be present with any dengue infection (Gubler and Meltzer 1999). The specific causes of DHF are somewhat uncertain, but it appears that a second dengue infection with a different serotype may increase the likelihood of developing DHF, illustrating the importance of preventing or limiting a future outbreak in Hawaii (Guzman and Kouri 2002). There is no specific treatment for the disease, but acetaminophen and fluid replacement therapy can be used to ease the symptoms of dengue; DHF often requires hospitalization (Centers for Disease Control and Prevention 2002). The case fatality rate for dengue fever itself is low, but when the number of deaths from DHF is included, the case fatality rate ranges from 1 percent to 5 percent (Halstead 1997). Finally, a major focus of research is the development of a dengue vaccine, which would protect against the four serotypes and would be highly cost-effective (Kroeger,

Nathan, and Hombach 2004; Stephenson 2005).

## Climate and Dengue

Although *Ae. albopictus* is likely to breed in artificial containers in and around dwellings, it is considered to be a forest-dwelling mosquito and prefers outdoor habitats to indoor or peridomestic environments; therefore its lifecycle is strongly affected by climate conditions (Kuno 1997; Rodhain and Rosen 1997). Previous research has established a link between dengue outbreaks and climate conditions in several locations (Kuno 1997), though in some cases it is contradictory. A positive correlation between the number of dengue epidemics in the South Pacific region and above-average rainfall has been recognized (Hales, Weinstein, and Woodward 1996), and the above-average dengue incidence experienced in Asia in 1998 was also found to be associated with above-average rainfall (Kovats 2000). In northeastern South America, however, a negative correlation was found between dengue epidemics and rainfall (Gagnon, Bush, and Smoyer-Tomic 2001). The vector in South America is *Ae. aegypti*, which more commonly breeds in artificial water containers than does *Ae. albopictus*, and it is hypothesized that during dry conditions, people may increase their use of rainwater collection containers, providing areas for *Ae. aegypti* breeding (Poveda et al. 1999; Pontes et al. 2000).

Temperature is another important variable to consider in dengue incidence; temperature affects both the mosquito's longevity and biting rate, and the rate of viral reproduction within the mosquito (Kuno 1997). Mosquitoes cannot survive below a certain temperature threshold, and the biting rate typically increases as temperatures increase (Chandler 1945). Higher temperatures can shorten the extrinsic incubation period (viral development rate) of the dengue virus within the mosquito; conversely, very high temperatures may actually shorten mosquito survival (Patz et al. 1998). Climate conditions are particularly important in this study because the tropical species of *Ae. albopictus* is nondiapausing, meaning that larvae do not enter a period of dormancy when temperature and moisture conditions are not conducive to survival, and the eggs are not able to survive (Hawley et al. 1987).

Given the relationship between mosquito habitat and climate, it is expected that the range of many mosquitoes, including the *Aedes* species, will be altered with climate change, possibly putting more people at risk for contracting dengue. Recent research has examined the potential for the spread of dengue into temperate parts of the world as the global climate warms (Patz et al. 1998; Hales et al. 2002). It is important to first grasp the relationship between dengue and climate variability before tackling the more difficult task of understanding how climate change will affect disease distribution given interrelationships between the two, and the research presented here will aid in this broad understanding.

## Conceptual Framework Development

A critical tool in attempts to control dengue is the modeling of mosquito habitat and dengue potential. The current conceptual framework used to develop mosquito and dengue models typically considers climate and other environmental variables as constant. Models are developed based on average conditions and rarely, if ever, consider seasonal and interannual shifts of climate or environmental variability. Even models incorporating environmental conditions under global change scenarios (Patz et al. 1998; Hales et al. 2002) consider shifts in variables without taking into account the continued variability and fluctuations that will occur under changed conditions. Research in climate and ecology over recent decades, for example, has highlighted that climate and the environment are characterized by change and variability, both temporal and spatial, and that the notion of a mean or "original" state is a flawed one. In climate, this is exemplified by the large and growing literature on El Niño/La Niña-related variability and on longer-term climate change (e.g., Houghton et al. 2001; McPhaden 2004).

The notion of shifts in mosquito and dengue endemic areas has been considered in studies of climate change impacts, and the impacts of El Niño have been considered as well; however, the outcomes of this work, while recognizing dynamic and complex processes controlling dengue, have themselves been fairly static results and products. For example, a stated shift in El Niño conditions is linked to a stated shift in dengue incidence (Hales, Weinstein, and

Woodward 1996; Kovats 2000). Previous studies have developed static mosquito habitat models, but the new conceptual framework presented here recommends the incorporation of a dynamic model (with respect to human and environmental variables) in future mosquito modeling research, which is more realistic and true to real-world situations.

**Study Area**

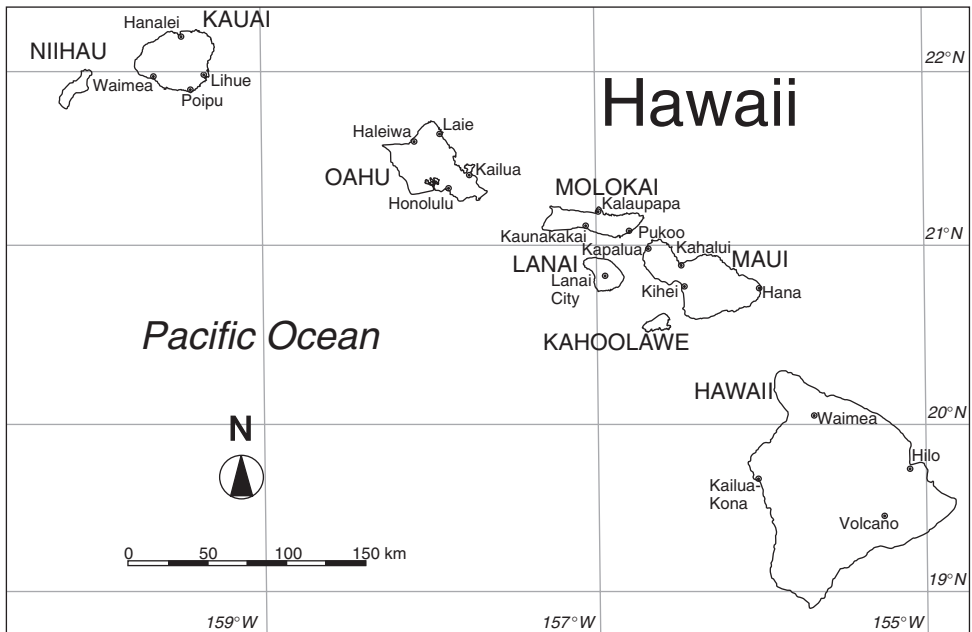
Hawaii is composed of a series of volcanic islands with varied topography and climate. Located between 19°N and 22°N (Figure 1), the islands are dominated most often by the tropical easterlies (trade winds), causing the windward eastern sides of the islands to receive more rainfall than the leeward western sides. Many areas on the leeward sides receive little rain and are classified as a desert, and areas on the windward sides are classified as tropical forests. Occasional wind shifts bring rain to the leeward sides of the islands, and, in rare cases, fronts pass over Hawaii, typically bringing rain to the north and western portions of the islands (Sanderson 1993).

**Data**

The datasets used in the building of GIS layers include both human and physical landscape features in Hawaii (Table 1). Spatial temperature and precipitation, perennial streams, and wetland data were used in the delineation of potential mosquito habitat, and the addition of populated areas supplemented the habitat map to create a dengue potential map.

Spatial climate information is a key variable in the determination of mosquito habitat. PRISM (parameter-elevation regressions on independent slopes model) data, spatial climate data developed using a knowledge-based system acquired from the Spatial Climate Analysis Service, are used in this study. Temperature and precipitation data are developed on a grid using station data, topography, and user input, and are verified using a variety of related spatial datasets such as satellite data (Daly et al. 2002). For Hawaii, PRISM data are available at a resolution of 450 m, and the analyses in this study use the average (1961–1990) monthly precipitation (Figure 2) and temperature (Figure 3).

Most previous studies have examined the specific extremes that decrease mosquito sur-



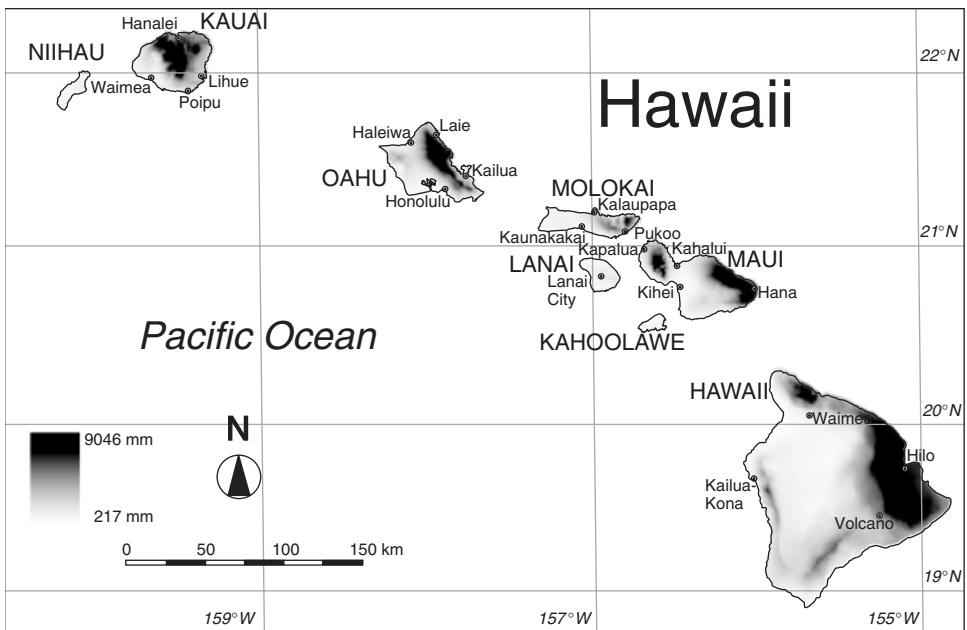
**Figure 1** Study area, with principal cities and towns.

**Table 1** Sources of spatial data

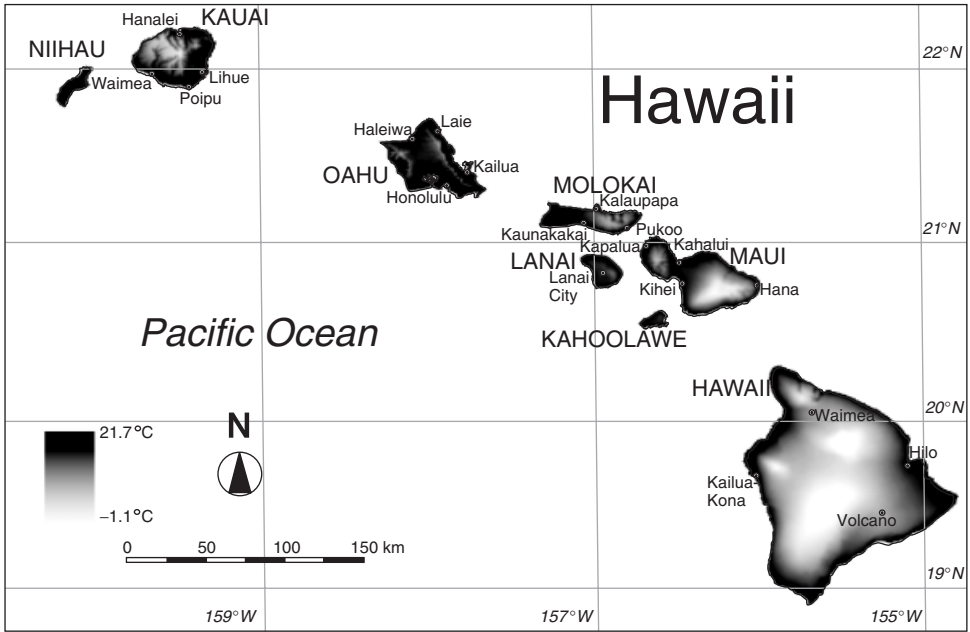
Dataset	Source	Additional information
Precipitation	Spatial Climate Analysis Services	Monthly and annual average, 450-m resolution, 1961–1990
Temperature	Spatial Climate Analysis Services	Monthly and annual average, minimum, and maximum, 450-m resolution, 1961–1990
Perennial streams	Hawaii State GIS Program ( <a href="http://www.hawaii.gov/dbedt/gis/">http://www.hawaii.gov/dbedt/gis/</a> )	From: USGS Digital Line Graphs, 1983 version; CWRM Hawaii Stream Assessment database, 1993
Land use/land cover (populated areas)	Hawaii State GIS Program ( <a href="http://www.hawaii.gov/dbedt/gis/">http://www.hawaii.gov/dbedt/gis/</a> )	From: 1976 Digital Geographic Information Retrieval and Analysis, 4-ha resolution
Wetlands	Hawaii State GIS Program ( <a href="http://www.hawaii.gov/dbedt/gis/">http://www.hawaii.gov/dbedt/gis/</a> )	From: National Wetlands Inventory Maps, 1978

vival; few studies have examined the typical climate conditions under which *Ae. albopictus* is able to survive, particularly in the tropics. Research focusing on the survival of larvae and the mosquito’s development to the adult stage has been conducted in a controlled environment within the laboratory (Hanson and Craig 1995; Alto and Juliano 2001a, 2001b; Briegel and Timmermann 2001), but direct field studies have been conducted as well (Tsuda and Takagi 2001) and these latter data provide the habitat thresholds for *Ae. albopictus* used in this study. Mitchell (1995) summarized research on *Ae.*

*albopictus*’s habitat in the Mediterranean region, and although data regarding the mosquito’s survival in the tropics would be ideal, such information is presently unavailable. Locations where *Ae. albopictus* has become established typically receive more than 500 mm of rainfall annually (Mitchell 1995). That value is used in the present study to determine the minimum annual precipitation required, but the value ignores *seasonal* precipitation receipt, a crucial variable in a location with varied climates such as Hawaii. The very dry summers experienced in leeward locations of Hawaii are unlikely to



**Figure 2** Average annual precipitation (1961–1990). (Source: Spatial Climate Analysis Services)



**Figure 3** Average annual minimum temperature (1961–1990). (Source: Spatial Climate Analysis Services)

permit the survival of the mosquito, even where average annual rainfall is at least 500 mm. Therefore, to fill that gap a seasonal precipitation variable is included in this study. Examination of the seasonal precipitation receipt across the islands shows that, on average, June is the driest month on the leeward side, so average June precipitation is used to determine the seasonal cut-off. Precipitation receipt of 40 mm during June, one-twelfth of the annual receipt of 500 mm, is used as the minimum threshold to establish a seasonal precipitation value. Specific thresholds are required to develop the model, but exact values are not critical given that the goal of the research is to develop a generalized mosquito habitat map.

Although temperature is an important factor in mosquito biting habits and in virus development within the mosquito, this study is not attempting to predict those factors, and temperature is used in this study to aid in the determination of potential habitat. Mitchell (1995) has reported that a monthly minimum temperature of 10°C during the coldest month is the approximate minimum temperature condition under which larvae can survive, and that value is

used as a cut-off in this study. Short-term temperature and moisture extremes affect the day-to-day survival of mosquitoes (Tsuda and Takagi 2001), but this study uses longer-term monthly data to delineate broad generalized mosquito habitat.

Depending on flow amounts, perennial streams can either provide mosquito habitat in the form of stagnant pools, or remove mosquito larvae during periods of high flow. The Hawaii Department of Health cited low streamflow along the northeastern coast of Maui as a contributing factor to the 2001–2002 dengue outbreak. Even though streams have the dual potential of increasing or decreasing overall mosquito populations, given the capability of streams to serve as mosquito habitat, they were included in this analysis. The approximate flight range of *Ae. albopictus* during its lifetime is 500 m (Rodhain and Rosen 1997), so a 500-m buffer was created around streams to account for the distance mosquitoes typically fly from their breeding grounds. Wetlands serve as a natural breeding ground for mosquitoes as well, and wetland locations were included in this study in the analysis of potential *Ae. albopictus* habitat. As

with perennial streams, the 500-m buffer was applied to the wetland data in order to approximate the flight distance from the breeding ground.

For the dengue potential map, populated areas were added to the model. Humans provide a breeding area for mosquitoes in the form of water vessels in and around the home, as well as a blood meal that can lead to the transmission of dengue. Data on populated areas were acquired from land use/land cover data, and consist of areas delineated as "urban or built-up land" such as industrial, commercial, and residential zones. This description of a populated area is broader than simply including residential areas; the model seeks to include places where people may be working as well as residing. Population density is not considered; instead, areas are delineated as "populated" or "not populated." Future iterations of the model attempting to delineate dengue potential at a finer scale will take population density into account.

Other data were considered for inclusion in the model but were not selected in the final iteration. Layers including garbage dump locations and information on human behavior regarding water storage are likely useful in a model delineating dengue potential but those factors operate on a smaller scale than the other variables included in the study. Vegetation cover was considered for inclusion in the model, given its importance in creating microclimatic conditions favorable for mosquito habitat (Mitchell 1995), but it was not selected for the final version because of the broader scale at which the model developed here operates. Also, the model developed in this study is intended to generally outline mosquito habitat and dengue potential areas rather than precisely pinpoint those regions. Future iterations of the model seeking to identify mosquito habitat areas at a finer scale will include a broader range of variables, including microclimatic data.

## **Methods**

Species habitat modeling predicts the geographic distribution of a species based on variables such as climate conditions, geologic characteristics, topographic features, and competition with other species. One example is predictive vegetation mapping, which seeks to develop a model for mapping vegetation based

on environmental variables and applies that model to produce a predictive map (Franklin 1995). Similar habitat modeling techniques can be applied to the modeling of many infectious diseases, which begin by predicting where the vector will be present. Studies have shown that modeling disease occurrence based on environmental conditions can be an effective way of developing a predictive spatial model. Studies have modeled the spatial distribution of diseases such as Lyme disease (Glass et al. 1995; Nicholson and Mather 1996; Brownstein, Holford, and Fish 2003), malaria (Beck et al. 1994, 1997; Hay et al. 2002; Rogers et al. 2002; Zhou et al. 2004), hantavirus (Engelthaler et al. 1999; Boone et al. 2000; Glass et al. 2000), and Rift Valley fever (Linthicum et al. 1999), as well as dengue. Many of these studies used gridded climate data and/or remotely-sensed data to determine vector habitat areas and then developed regression-based predictive models. Such models provide a starting point for vector-control programs as well as outbreak-control should a pathogen be circulating through the vector population. Albert (2000) summarized infectious disease studies that use GIS in modeling efforts and suggests that the integration of physical and human geographic perspectives in disease modeling is necessary to more completely delineate risk areas. The study presented in this article seeks to follow this recommendation and improve on the methods of past studies of infectious disease by including human features in addition to environmental factors, and by designing predictive maps that respond to user inputs.

Previous studies have developed dengue potential maps on both a global scale and regional scales. Patz et al. (1998) and Hales et al. (2002) examined the possible change in the global distribution of dengue based on climate and population change, and risk maps have been developed at the country scale for Argentina (Carbajo et al. 2001) and New Zealand (de Wet et al. 2001) with environmental and social features as input. Napier (2003) examined dengue risk in Hawaii but did not use the relatively fine-scale gridded climate data (450 meters) used here, nor were mosquito survival thresholds applied in that study. Also, the maps developed in other studies were static, whereas those developed here are designed to be adjustable based on the input and knowledge of expert users.

In this study, methods similar to those employed in other disease modeling studies are incorporated into the model development. Mosquito habitat and dengue potential maps are created using an overlay analysis in which the layers are combined using constraints (Eastman 1997). The development of a dengue potential map of Hawaii first requires the delineation of potential mosquito habitat. The mosquito habitat map outlines the area with suitable environmental conditions to support a population of *Ae. albopictus* based on survival thresholds. Locations across the islands that meet the threshold requirements for the mosquito for both temperature and precipitation are delineated, and the 500-m stream and wetland buffer layer is overlain on the temperature and precipitation areas to further define mosquito habitat. Then, through the addition of human features on the landscape, a dengue potential map is created. A dengue outbreak is not likely to occur simply where the mosquito is present, but rather near people, given that it can breed in artificial containers and requires a blood meal for stages of the lifecycle. Therefore, populated zones are added as areas where the

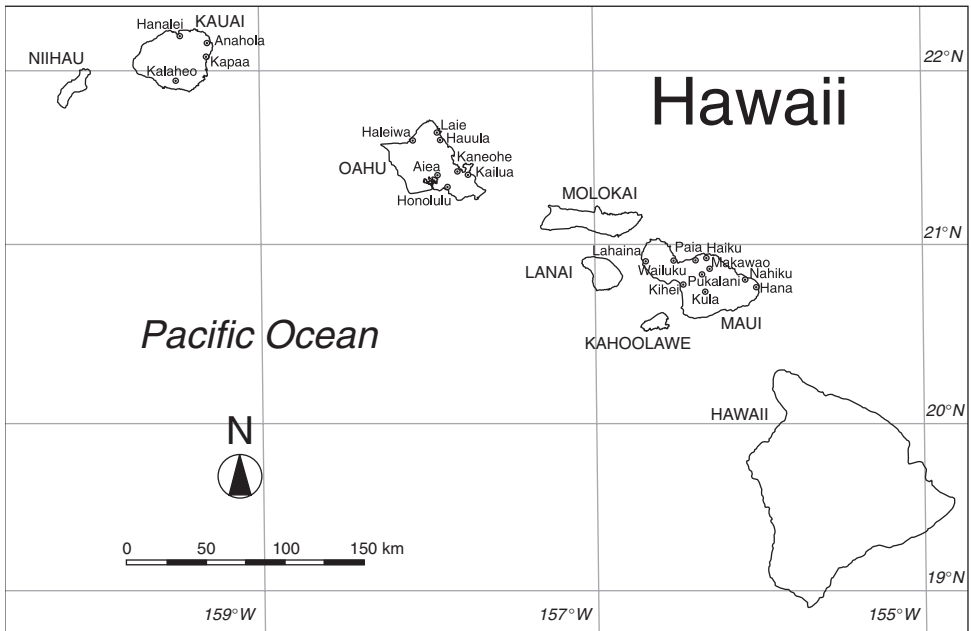
mosquito might breed near humans and acquire a blood meal, thus possibly transmitting the dengue virus.

Validation of the model and map requires a spatially representative sample of mosquito surveillance data across the islands, which is currently unavailable. For this study, the maps were validated using case location data from the 2001–2002 outbreak (Figure 4). Admittedly it is not ideal to use disease data to assess potential mosquito habitat, however similar methods of validation have been used successfully in the absence of mosquito surveillance data (Hopp and Foley 2003). The map is not intended to provide the precise potential location of mosquitoes, rather a generalized habitat area, so the town-level independent data used for validation is at an appropriate scale.

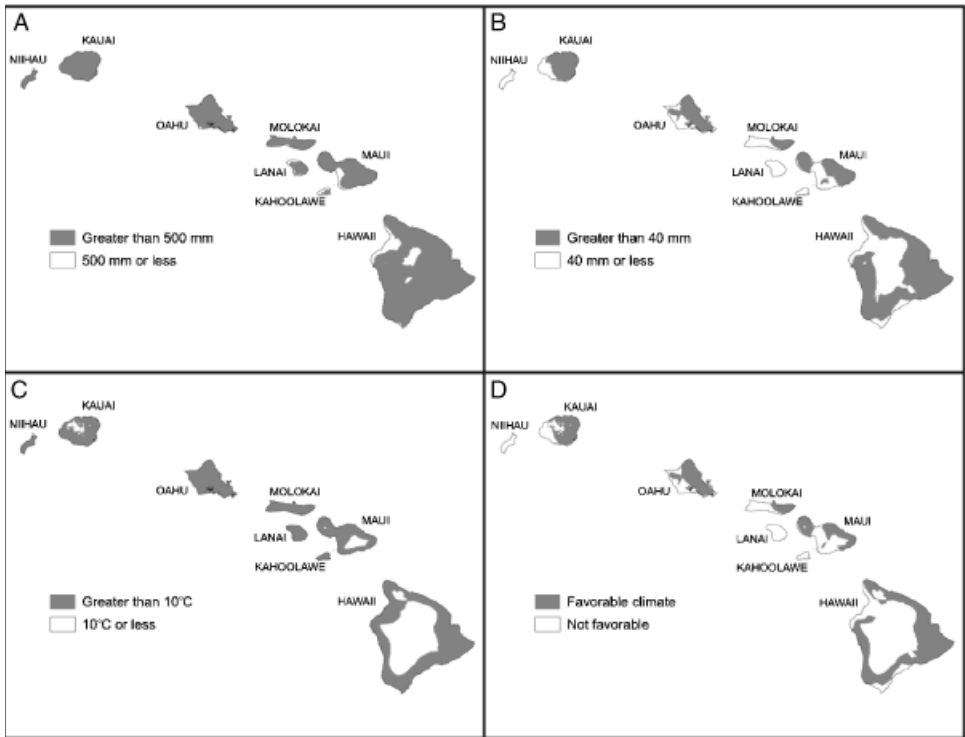
## Results

### Potential Mosquito Habitat

Most of Hawaii receives at least 500 mm of precipitation annually, with the exception of low-lying, leeward areas on Maui, Lanai, Kahoolawe



**Figure 4** Case locations of the 2001–2002 outbreak, used in this study for validation. (Source: Hawaii Department of Health)



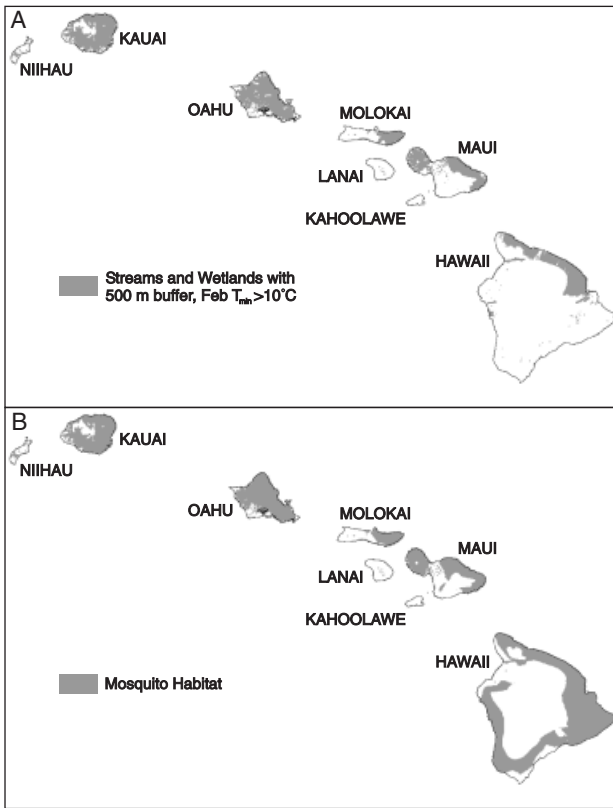
**Figure 5** Areas with average annual precipitation greater than 500 mm (A), average June precipitation greater than 40 mm (B), and average February minimum temperature greater than 10°C (C). Part (D) shows areas meeting the climate thresholds for *Ae. albopictus* survival, the intersection of A, B, and C.

(uninhabited), and the island of Hawaii (Figure 5A). Many leeward locations that receive at least 500 mm of precipitation on average experience extremely dry summers (Kolivras and Comrie forthcoming) and are therefore unlikely to serve as mosquito habitat. The seasonal precipitation threshold, average June precipitation greater than 40 mm (Figure 5B), delineates areas with acceptable precipitation levels for mosquito survival, and eliminates the driest locations from consideration. Most leeward locations are removed from potential habitat, with the exception of areas on Maui and Hawaii (the Big Island) given that topography and the climate are more varied on those islands.

The spatial pattern of the temperature threshold is mainly a function of elevation, and the highest elevation locations fall below the level of a minimum temperature of 10°C during February and are excluded from potential habitat (Figure 5C). The relatively low-lying

islands of Niihau, Oahu, Molokai, Lanai, and Kahoolawe do not experience minimum February temperatures below the threshold, but high points on Kauai, Maui, and the island of Hawaii are removed from potential habitat. The final climate map, Figure 5D, is the intersection of Figures 5A, 5B, and 5C, and highlights those areas with suitable temperature and precipitation levels to potentially provide mosquito habitat.

Perennial streams and wetlands may provide mosquito habitat in areas that are otherwise not conducive to mosquito survival given low precipitation receipt. In Figure 6A, streams and wetlands with a 500-m buffer for both features are overlain with areas that have suitable temperature conditions for mosquito survival. Mosquitoes could survive in a wetland even if overall precipitation receipt is low, but temperature is still a limiting factor. Therefore, wetland and stream buffer areas that are below the temper-



**Figure 6** Areas within 500 m of a stream or wetland, where average minimum temperature in February is greater than  $10^{\circ}C$  (A) and potential mosquito habitat map developed from a union of climate thresholds (Figure 5D) and stream and wetland buffer areas (B).

ature threshold for mosquito survival have been excluded.

*Dengue Potential*

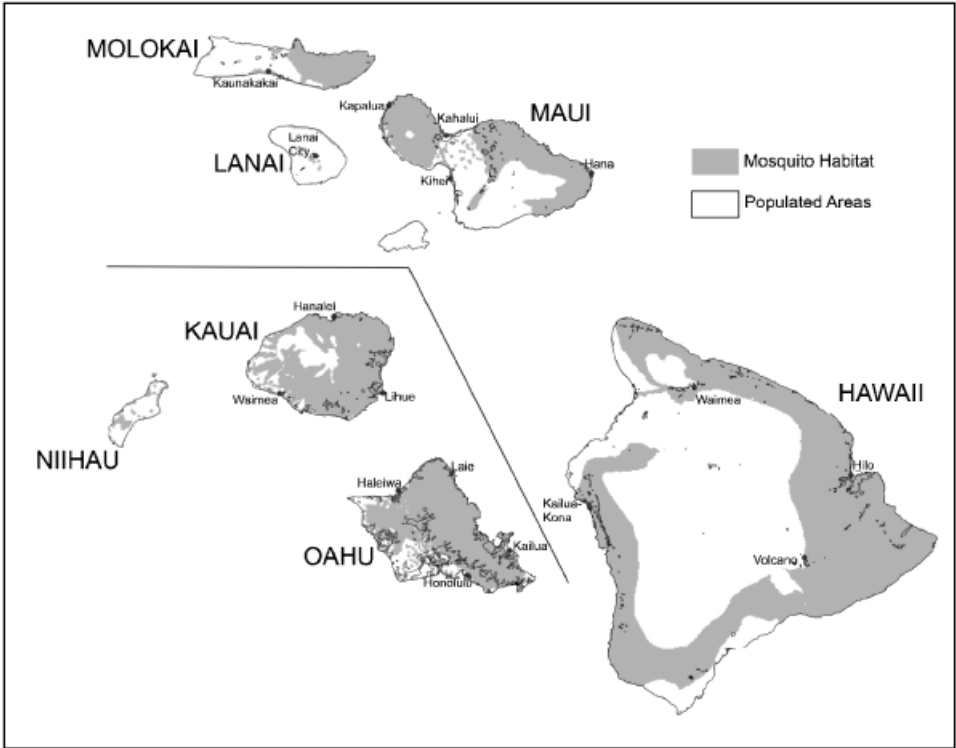
A single static habitat map (Figure 6B) was created from a union of the factors of precipitation, temperature, stream, and wetland location, and populated areas were added to determine locations that are more likely than others to experience dengue transmission if the virus were introduced (Figure 7). Hawaii’s population is concentrated near the coast, and with the exception of dry leeward locations, many populated areas are within the mosquito habitat zone.

*Adjustable Mosquito Habitat Maps*

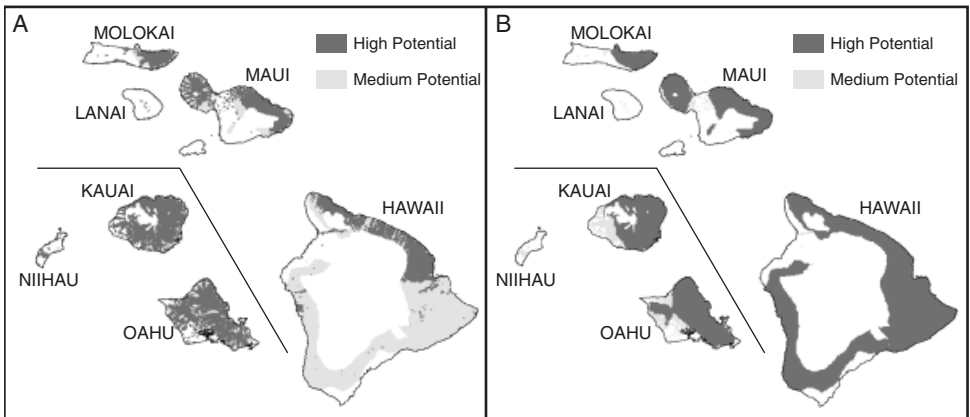
By emphasizing different variables on the static habitat map (Figure 6B), adjusted habitat maps can be created by public health decision-makers (e.g., mosquito control experts or epidemiologists) based on user preference and expert local

knowledge in order to visualize habitat areas differently. Two sample maps have been created as examples, the first emphasizing proximity to streams and wetlands and the second focusing on climate thresholds.

To develop the stream/wetland-emphasis map (Figure 8A), those areas within 500 m of a stream or wetland are designated high dengue potential. Locations within the area meeting the climate thresholds are considered in this example to be medium potential zones. Similarly, the climate emphasis map (Figure 8B) prioritizes areas that have a suitable climate for mosquito habitat as high dengue potential, and areas near a stream or wetland are designated medium potential. Using these maps, mosquito control resources could be concentrated in areas near streams and wetlands or in suitable climate areas, depending on the expert opinion of local public health and mosquito control officials.



**Figure 7** Dengue potential areas, developed by overlaying the mosquito habitat map (Figure 6B) and populated areas.



**Figure 8** The stream/wetland-emphasis potential map (A) weights streams and wetlands (high) as higher mosquito potential areas than regions within the climate threshold area (medium). The climate-emphasis potential map (B) weights areas within the climate threshold area (high) as having a higher mosquito potential than areas within the 500-m stream and wetland buffer area (medium).

**Table 2** Validation of mosquito habitat

Within climate threshold area		Outside climate threshold area
Anahola, Kauai	Paia, Maui	Kihei, Maui
Hanalei, Kauai	Pukalani, Maui	Lahaina, Maui
Kalaheo, Kauai	Wailuku, Maui	Haleiwa, Oahu
Kapaa, Kauai	Aiea, Oahu	
Haiku, Maui	Hauula, Oahu	
Hana, Maui	Honolulu, Oahu	
Kula, Maui	Kailua, Oahu	
Makawao, Maui	Kaneohe, Oahu	
Nahiku, Maui		

Within stream/wetland threshold area		Outside stream/wetland threshold area
Anahola, Kauai	Paia, Maui	Kula, Maui
Hanalei, Kauai	Wailuku, Maui	Pukalani, Maui
Kalaheo, Kauai	Aiea, Oahu	
Kapaa, Kauai	Haleiwa, Oahu	
Haiku, Maui	Hauula, Oahu	
Hana, Maui	Honolulu, Oahu	
Kihei, Maui	Kailua, Oahu	
Lahaina, Maui	Kaneohe, Oahu	
Makawao, Maui	Laie, Oahu	
Nahiku, Maui		

### Spatial Pattern Validation

The majority of towns that had cases during the 2001–2002 outbreak are located within the climate threshold area and the streams/wetland area. Of the twenty-one towns with cases, eighteen are within the climate threshold area and nineteen are within the streams/wetland area (Table 2). In the absence of mosquito surveillance data, which would more accurately validate the model, case locations suggest that the mosquito habitat maps represent areas of potential dengue transmission, and a concentration of health department resources in those regions could have an impact on preventing and controlling future outbreaks.

### Discussion and Conclusion

This study has identified mosquito habitat and dengue potential areas in Hawaii. Examining climate alone, low and middle elevation windward locations often serve as appropriate mosquito habitat, and leeward and high elevations are typically too dry or too cold, respectively, for mosquito survival. The inclusion of stream and wetland locations recognizes areas outside of the climate threshold zones in which mosquitoes could breed. From an applied standpoint, the maps developed for Hawaii can change and adapt based on user inputs, which will aid in

mosquito surveillance and outbreak prevention. Future work will apply the improved conceptual framework presented earlier to examine the shifts of mosquito habitat in Hawaii with climate variability and change. In addition, future iterations of the model presented here will be improved with more sophisticated modeling techniques, such as the genetic algorithm for rule-set prediction (GARP), which has been successfully used for ecological niche modeling in general (Peterson 2001) and for modeling of the *Triatoma* species, the vector for Chagas' disease (Costa, Peterson, and Beard 2002; Beard et al. 2003).

The conceptual framework developed in this study illustrates research gaps in the area of mosquito habitat modeling. The improved conceptual framework can be applied to future research studying the dynamic and complex role that environmental variables play in the creation of mosquito habitat. Environmental conditions are characterized by variability and change, and mosquito models based on environmental variables need to reflect that perspective. Future work will concentrate on examining how climate variability results in an expansion or contraction of potential mosquito habitat. The results of a study examining precipitation variability at the sub-island level (Kolivras and Cormie forthcoming) will be applied to the results of this research to study how mosquito habitat may be modified with varied precipitation at both seasonal and interannual temporal scales, including the effect of El Niño/La Niña on mosquito habitat in Hawaii. Under average conditions, windward locations receive consistent precipitation year-round, thereby supporting mosquito growth throughout the year. Leeward locations (with the exception of the leeward Big Island of Hawaii) receive precipitation mainly during winter, and are relatively dry during summer (Sanderson 1993). It is expected that although leeward locations may be too dry on average for mosquito survival, seasonal conditions may be conducive to mosquito growth during the relatively wetter winter.

On an interannual basis, the El Niño-Southern Oscillation could potentially affect mosquito habitat in Hawaii, and future work will examine the effect of climate variability driven by El Niño and La Niña. A drought, whether associated with El Niño or not, may lead to the formation of stagnant pools in streams on the

windward sides of the islands, which would be an attractive breeding area for mosquitoes. Since the impact of El Niño/La Niña is consistent across the islands (Kolivras and Comrie forthcoming), an El Niño-associated drought may result in increased mosquito habitat on the windward sides of the islands through the creation of standing pools in streams. This drought would likely cause the leeward sides to be too dry at any point during the year to support mosquitoes. Conversely, above-average rainfall during La Niña events could produce the opposite effect—the creation of mosquito habitat on the typically dry leeward sides, and the elimination of potential habitat in windward locations as increased stream flow removes larvae from breeding sites.

Given the importance of microclimatic conditions in the determination of habitat, better fine-scale information on mosquito survival in the tropics is required to decrease uncertainty in future studies. The research presented here was limited by the absence of spatial mosquito surveillance data across the islands to develop and validate a fine-scale model, and regular surveillance can improve modeling as well as inform public health officials of the changing nature of mosquito distribution and timing for improved mosquito and disease control.

The adjustable nature of the maps developed in this study allows users with expert knowledge of a place to adjust the input factors to develop a more precise map depending on local conditions. In fact, even with improved models and mosquito surveillance data, there is still no canonical “right” map. Thus, the opportunity for expert interaction is useful. In this framework, the results of this study serve as a generalized decision-support mechanism rather than as an attempt to define precisely where mosquitoes and potential dengue outbreaks will be. By modifying inputs through a variable weighting process, decisions regarding mosquito and disease control can be adjusted based on specific temporal and local spatial variation. Another future research direction will involve interviewing the various stakeholders active in decision-making regarding mosquito and dengue control, such as epidemiologists, vector control specialists, and health department officials. One potentially useful follow-on to this study is to implement the analytic hierarchy process, a decision-support methodology that incorporates

multiple criteria into a model and discriminates between the specific preferences of various experts based on personal knowledge of the system (Saaty 1987). In the case of mosquito/dengue control, the input variables to the maps developed in this study can be weighted and adjusted in importance in the model based on the preferences of decision-makers, and new maps can be developed similar to the sample adjustable maps produced in this study.

The maps created in this study are useful to stakeholders in Hawaii who are attempting to control mosquitoes and dengue. The conceptual framework developed here can be used to further study mosquito-environment relationships in Hawaii and elsewhere involving other vector-borne diseases. In future research, by adding the concept of dynamism and variability into previously static mosquito models, fluctuations in populations with environmental variability can be more closely estimated. Eradicating mosquito-borne diseases is highly unlikely, but understanding the interacting environmental factors related to mosquito habitat will greatly improve disease control and will allow health departments to concentrate limited financial and personnel resources in appropriate areas. ■

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