Development and Validation of a Remote Sensing Model to Identify Anthropogenic Boreholes that Provide Dry Season, Refuge Habitat for Anopheles Vector Mosquitoes in Sub-Saharan Africa

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Development and Validation of a Remote Sensing Model to Identify Anthropogenic Boreholes that Provide Dry Season, Refuge Habitat for Anopheles Vector Mosquitoes in Sub-Saharan Africa

by

James P. Kukat

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Public Health Department of Global Health College of Public Health University of South Florida

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Keywords: Dry-seasonal rivers, Interpolating a spectral signature, Tropical savanna climate

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DEDICATION

With sincere gratitude, I wish to express much appreciation to my brother, Mike Kukat, and sister, Nancy Kukat, for tirelessly carrying out mosquito sampling in anthropogenic borehole habitats since the inception of this project in January 2015 through the end in June 2015. Your treasured contribution is much appreciated and without it, this project would not have been attainable. This thesis is dedicated to you. Finally, but not the least, this thesis is dedicated to my Pokot community living in the malaria endemic environment of Chemolingot, Kenya and to others in the tropics where malaria afflicts the most.
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I would also like to recognize the DigitalGlobe Foundation for their understanding of the need to solve health issues transcending national boundaries and for providing me with the high resolution satellite imagery necessary to carry out this research. I am truly appreciative of your assistance and without your data, imaging of anthropogenic boreholes would not have been possible.
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ABSTRACT

A lack of surveillance systems is an impediment to public health intervention for perennial vector-borne disease transmission in northern tropical savanna region of Kenya. The population in this area are mostly poor nomadic pastoralists with little acquired functional immunity to *Plasmodium falciparum*, due to infrequent challenges with the parasite. A common characteristic in tropical savanna climatic zone is the availability of riverbeds that have anthropogenic boreholes that provide malaria vector mosquitoes, such as *Anopheles gambiae* s.l and *Anopheles funestus*, with aquatic refuge habitats for proliferation and endemic transmission to proximity human households during the dry-season. Unfortunately, currently there have been no entomological investigations employing field or remotely sensed data that can characterize and model anthropogenic borehole habitats focusing on the dry-land ecology of immature *Anopheles* mosquitoes in sub-Sahara Africa. The goal of this investigation was three-fold: (I) to employ WorldView-3 (0.31 meter spatial resolution) visible and near infra-red waveband sensor data to image sub-Saharan land cover associated with vector-borne disease transmission; (II) to remotely identify anthropogenic boreholes in three riverbeds that were surveyed to determine whether they provide malaria vectors with refuge habitat and maintain their population during the dry season in Chemolingot, Kenya, and (III) to obtain a radiometric/spectral signature model representing boreholes from the remotely-sensed data. The signature model was then interpolated to predict unknown locations of boreholes with the same spectral signature in Nginyang Riverbed, Kenya. Ground validation studies were subsequently conducted to assess model’s precision based on sensitivity and specificity tests.
CHAPTER ONE:
INTRODUCTION

In the tropical savanna region of sub-Saharan Africa, malaria vectors are faced with highly variable, and challenging climatic conditions (Mattingly, 1971); protracted dry seasonal climatic constraints affect their seasonal productivity. A common characteristic of the tropical savanna ecosystem is the presence of seasonal rivers which have anthropogenic boreholes that provide local communities (mainly nomadic or semi-nomadic pastoralists) with a year-round primary source of water for domestic usages and watering of livestock. However, unfortunately, these boreholes, can impart malaria vectors with opportunistic refuge habitat for proliferation, and capacity to transmit disease to proximity human households.

Malaria is the most important vector-borne disease in Kenya; in terms of high morbidity and mortality it causes, and poor economic implications it promotes. According to the country’s National Malaria Control Program (NMCP) (NMCP, 2015), the disease accounts for 15% of all outpatient attendance in health facilities admissions. This prevalence, is contributed by the seasonal epidemic transmission experienced in arid and semi-arid areas of northern and south-eastern parts of the country, where short periods of intense transmission occur during the rainy seasons; however, malaria is endemic throughout the year (NMCP, 2015). Studies conducted by Coetzee, Craig & le Sueur (2000), have established that high levels of malaria transmission frequently occur where both Anopheles gambiae sensu lato (Anopheles arabiensis and Anopheles gambiae sensu stricto, the two main species of the seven siblings, which vector malaria) and
Anopheles funestus are present, as they tend to exploit different breeding habitats and peak at different times, therefore prolonging the transmission period of malaria. Generally, Anopheles gambiae s.l. species are most abundant during the rainy season (except Anopheles arabiensis, which is more common in zones with less rainfall), while Anopheles funestus is predominant at the end of the rainy season and beginning of the dry season (Coetzee, Craig & le Sueur, 2000).

In the northern tropical savanna climate of Kenya, seasonal rivers provide malaria vectors with water for most of the year, therefore, ensuring year-round, low-level transmission of malaria (Mala et al., 2011). A common characteristic in the tropical savanna ecosystem is the sudden shrinking or complete disappearance of larval habitats during the dry season, which is followed by a rapid drop in abundance of malaria vectors, and a concomitant decrease in the incidence of severe malaria (Snow et al., 1993; Wilkinson, Goulds, Boonyakanist & Segal, 1978). The onset of both long and short rains result in flooding of rivers and the creation of temporary vernal pools, which exponentially increases vector populations and consequent hyper-epidemicity of malaria (Mbogo et al., 1993; Omer, & Cloudsley, 1968; Omer, & Cloudsley, 1970). However, it is uncertain whether the initial vector population buildup at the onset of rainfall results from a new population of immigrant mosquito vectors from neighboring areas with more permanent larval habitats, or expansion from a very small local population that survives the dry season (Mala et al., 2011).

A similar ecological condition like the one experienced by mosquito vectors in tropical savanna climate occurs in the sub-Saharan country of Eritrea. The semi-arid climate experienced in Eritrea’s provinces of Anseba, Gash-Barka, Debub, and North Red Sea, provide malaria vectors with a challenging eco-biological environment for survival; however, endemic malaria is prevalent in these provinces (Novak & Shililu, 2007). Novak & Shililu (2007) found that rivers and streams have surface water only during the later stages of the rainy seasons; this is the time frame for
increased vector abundance and malaria transmission. However, a low-level of malaria transmission does occur during the extensive dry season (Novak & Shililu, 2007). Later studies by Jacob et al (2008) in Uganda, another sub-Saharan country with a tropical savanna climate, geolocated clusters of productive *Anopheles arabiensis* aquatic habitats in dry river beds that were adjacent to camps of internally displaced people. Ecological sampling studies conducted in Marigat, Baringo County, Kenya by Mala et al (2011), showed *Anopheles arabiensis* as the dominant vector of malaria along with *Anopheles funestus* in this tropical savanna climatic town.

Remote sensing techniques have great potential in studies of malaria. According to Cline (1970), the use of remote sensing techniques to investigate mosquito and malaria ecology stems from the appreciation that aerial and space-borne sensors could provide relevant surrogate information relating to spatiotemporal variation in meteorological and vegetation-related covariates. Recent advances in space technology have resulted in increased public access to remotely sensed data that provide a cost-effective and efficient alternative to examine the relationships between climate, the environment, and mosquito vectors; this has rejuvenated malaria control efforts (Hay, Omumbo, Craig & Snow, 2000).

Results from past applications of remote sensing in vector ecology have been promising; Clennon et al (2010), employed the LandSat TM 5 sensor to identify potential mosquito vector sites in Mapanza Chiefdom, Southern Zambia that were likely to retain water after the rainy season. LandSat TM 5 imagery predicted aquatic habitats that *Anopheles* mosquitoes (specifically, *Anopheles arabiensis*) could inhabit. Mbogo et al (2003) retrospectively analyzed the spatial abundance, distribution and transmission data on *Anopheles gambiae s.l.* and *Anopheles funestus*; this study compared climate, vegetation, and elevation data derived from remote-sensed satellite sources in key study sites in Malindi, Kilifi, and Kwale Districts of Kenya. Jacob et al
(2009) employed QuickBird (0.61 meter spatial resolution imagery data) to remotely quantify sampled *Anopheles arabiensis* larval habitat covariates obtained from a rice-village complex in Karima, Mwea Rice Scheme, Kenya. This study confirmed Gu & Novak’s (2005) previous assertion that treatments or vector habitat perturbations should be based on surveillance of larvae in the most productive areas of an ecosystem.

The availability of freely downloadable satellite sensor data is important for vector control operations, especially in poorly resourced regions of the world, such as sub-Saharan Africa, where the collection of reliable ground data over large geographical areas is unattainable. However, the use of low resolution sensor data, such as those freely available online, or unradiometrically corrected images for pixel accuracy to generate remote sensing models that predict habitats for various tropical diseases have limited spectral capabilities, and can be inaccurate.

The goal of the current investigation was three-fold: (I) to employ WorldView-3 (0.31 meter spatial resolution) visible and near infra-red waveband sensor data to image sub-Saharan land cover associated with vector-borne disease transmission; (II) to remotely identify anthropogenic boreholes in three riverbeds that were surveyed to determine whether they provide malaria vectors with refuge habitat and maintain their population during the dry season in Chemolingot, Kenya, and (III) to obtain a radiometric/spectral signature model representing boreholes from the remotely-sensed data. The signature model was then interpolated to predict unknown locations of boreholes with the same spectral signature in Nginyang Riverbed, Kenya. Ground validation studies were subsequently conducted to assess model’s precision based on sensitivity and specificity tests.
CHAPTER TWO:
MATERIALS AND METHODS

Model Development

This study was conducted in Chemolingot, Baringo County, Kenya (latitude 0.590° North and longitude 35° East), a tropical savanna ecotone inhabited by the marginalized Pokot community, who are primarily nomadic pastoralists (Figure 1). Chemolingot is about 320 kilometers northwest of Nairobi, the country’s capital, and has a total population of 3,632 based on 2009 national census data from the Kenya National Bureau of Statistics (2015). Baringo County, which provides services to Chemolingot residents, and also the administrative division of Rift-Valley state, is a malaria endemic zone and transmission occurs year round (Aniedu, 1997).

Three seasonal rivers in the study site, Churtuten (approximately 5 km course), Karuwon (approximately 5 km course), and Cheptokokwo (approximately 8 km course), were chosen based on their nearness to human residences and the availability of year-round anthropogenic boreholes in their riverbeds. The three rivers are tributaries to Nginyang River (situated 8 kilometers south-east of Chemolingot), which drains into Lake Turkana in the North. The former was used to validate a remote sensing model that was developed in this study. These rivers are characterized by seasonal flooding in April and May and become dry between December and April when rain is scarce and borehole hydrology infiltrates the aquifer. Bedrock and sandy soils comprise most of the river hydrology, which combine a low percolation rate, longer residence time to produce a habitat conducive for Anopheles vector development in boreholes (Figure 2).
Figure 1: The study site in Chemolingot and topographical vector features georeferenced; topographical features (major roads and water) and administrative boundaries were obtained from http://www.wri.org/our-work (Washington, DC 20002, USA). Georeferencing was explored through Environmental Systems Research Institute (ESRI) ArcGIS 10.3.1 cyber-environment (ESRI, Redlands, CA, USA).

Chemolingot’s landscape consists of rolling plains. The average altitude is approximately 900 meters (1,558 meters and 809 meters are highest and lowest peaks, respectively), and it encompass tropical savanna vegetation with densely spaced, tall acacia trees, and bush along the rivers. The open pastureland is composed of thorn-brush and scattered thick-brush. Nomadic pastoralist’s village huts (located at the outskirts of the town), semi-permanent housing (near the town) and permanent housing (within, and at the center of the town) cluster around Chemolingot. Villages are scattered and mostly situated on high grounds or by the mouth of the rivers where
fertile soils yield greener pastures and water is nearby. Pokots relocate seasonally and tend to settle closer to boreholes that are known to exist and which provide water longer into the dry season (i.e., boreholes that do not have to be dug often). Water is fetched and stored in household containers for domestic use (e.g., cooking, washing, etc.) and/or watering animals, such as newly born lambs, camels or goats. The availability of water in these storage containers can in-turn, provide malaria vectors with proximity aquatic habitat for larval development.

**Figure 2**: Cartographic representation of the study site in Chemolingot. Landscape and distance approximation of Churtuten, Karuwon and Cheptokokwo rivers course is shown.
The annual climatic averages, indicative of tropical savanna, are 26 °C and 54 mm for mean temperature and precipitation, respectively (Free Climate Data for Ecological Modelling and GIS). Data for recent conditions (~1950-2000) were accessed from http://www.worldclim.org/current, and interpolated from sampled boreholes sites on November 15, 2015. Distinct wet and dry seasons occur in Chemolingot; rainfall is bimodal and occurs in the months of April and May (short rainy season), and July to September (long rainy season). In contrast, a long dry period, which is characterized by high temperatures and strong dusty winds, is experienced from December to April. During the dry period, scanty or totally absent precipitation is experienced. These harsh climatic conditions contribute to a rapid loss of transient mosquito larval habitats and ensures that only seasonal water sources (especially anthropogenic boreholes), remain the foci of malaria vectors (Mala et al., 2011).

The impact of meteorological factors on sub-Saharan Africa malaria vectors was studied by Paaijmans (2008), and the Anopheles vector mosquitoes sampled by Mala et al (2011) in the dry-land ecology of Baringo County. Anopheles arabiensis were sampled in higher densities than Anopheles funestas in Kamarimar and Tirion, Baringo, Kenya during the months of January and February when dry weather conditions are experienced. Anopheles larval sites (marshes, anthropogenic water dams, irrigation canals), sustained the two malaria vectors, formed the basis for field identification and observations of Anopheles larvae in borehole habitats. According to Paaijmans (2008), after hatching, Anopheles larvae lie horizontally just below the air-water interface, which makes them distinguishable from other mosquito species, such as Aedes and Culex, which hang vertically.

Anthropogenic boreholes in the three rivers were surveyed to determine whether they provide malaria vectors with refuge habitat and maintain their population during the dry season. Boreholes
were sampled bi-weekly from January 2015 to June 2015, since this was a timeframe for extended dry weather conditions in Chemolingot and mosquito larvae tend to be accessible. Boreholes were inspected for aqua-terrestrial, horizontally lying *Anopheles* larvae by two trained entomologists who trekked along the rivers to find new boreholes, and to resample old sites. Initially, data were recorded using a pen and a paper prior to being input into a computerized system. A digital photo of each sampled borehole was also taken. Boreholes were categorized dichotomously (e.g., zero represented absence of *Anopheles* larvae; 1 represented presence of any count of larvae above 0).

To geographically locate anthropogenic borehole habitats, a handheld Global Positioning System (GPS) unit was used to obtain precise coordinates of each borehole point. The GPS (Garmin Ltd., Olathe, KS, USA), was placed at the center of each borehole and the longitude (x) and latitude (y) coordinate pairs were recorded. The GPS data was then exported into ArcGIS 10.3.1 where ArcGIS geoprocessing tool, GPX to features, which converts point information inside a GPX file (handheld GPS) into a feature class, was employed. The outputted attribute table described fields for the shape, time, and elevation of each surveyed borehole. World Geodetic System (WGS) 1984 coordinate system was then used to set the spatial reference.

**Figure 3** depicts the state of an anthropogenic borehole in Cheptokokwo River site, with the bedrock and sandy soil conditioned to hold water in the dry season (Photo taken on June 14, 2015). **Figure 4 and Figure 5** show digital photographs of anthropogenic borehole habitats of *Anopheles* mosquitoes. **Figure 4** shows a deep, actively used borehole in Cheptokokwo River with a fetching container. **Figure 5** show dry, abandoned, shallow boreholes in Churtuten River.
Figure 3: Borehole in Cheptokokwo with underlying surface bedrock.
Figure 4: An actively used borehole in Cheptokokwo River with a fetching container.
Figure 5: Dry, abandoned, shallow boreholes in Churtuten River.

WorldView-3 satellite sensor data was used to image land cover types and to remotely determine the geographical locations of anthropogenic boreholes. The remote sensing data had 0.31 meter panchromatic 450-800 nm band resolution and 1.24 meter 8 band (red, red edge, coastal, blue, green, yellow, near-infrared_1, and near-infrared_2 400-1040 nm) multispectral resolution. The images were remotely taken over Chemolingot on January 12, 2015 (dry season), and contained 35 km$^2$ of the land cover in the study site. The satellite operated at an altitude of 617 km and collected 680,000 km$^2$ of ground data per day with an average revisit time of less than a day. The radiometrically corrected image pixels were delivered in a GeoTIFF file format, and with an orthorectified map scale of 1:12,000 from Digital Globe Inc. (Longmont, CO, USA). Upon
import to ArcMap, image composites were analyzed and found to have no cloud cover (0% cloud cover).

The maximum likelihood classification in ArcGIS was employed to execute image classification based on signatures obtained from multispectral band imaging of known land cover training sites with known class labels (e.g., Barren Land, Water Body, Riverine Vegetation, Built Environment, and Savanna Vegetation in Figure 5). In this probabilistic outcome, the remote sensor data was subdivided into two major phases: calibration, in which the ArcGIS built-in algorithm identified a classification scheme based on signatures of different bands obtained from known training sites with known class labels; and prediction, in which the classification algorithm based on a priori probability file in ASCII format or training samples was applied to find other imaged sites with unknown signature classification membership based on known, sampled signatures (Jacob et al., 2013).

The remote sensing images analyzed in the preliminary maximum likelihood classification step were then used to obtain a radiometric/spectral signature representing anthropogenic borehole habitats. All surveyed boreholes were analyzed in ArcGIS and the most productive in terms of availability of larvae throughout the sampling period was identified for signature extraction (Jacob, Mwangangi, Mbogo & Novak, 2011). Radiometric/spectral signature values were obtained by interactive supervised image classification process in ArcGIS; whereby training samples (mainly soils and water) of the productive borehole, were polygonised, merged, and their Red, Green, Blue, and Infrared_1 band values generated.
Figure 6: A maximum likelihood classification system of land use land cover (LULC) analyses for the Chemolingot study site in ArcGIS.

In the ArcGIS cyber-environment, the geostatistical analyst tool was employed to validate the ability of the radiometric/spectral signature model in forecasting the locations of unknown borehole sites. The process of creating the remote sensing prediction model involved the application of ArcGIS geostatistical analyst tool “Extract Values to Table,” which interpolated all
sampled boreholes to provide value predictions at the sampled borehole locations. Indicator prediction, based on the signature values, was then employed to identify boreholes in the remote sensing data of new sites, and to model the probability of predicted boreholes exceeding the threshold for productivity of *Anopheles* vector larvae. Empirical evidence from “ground-truthing” surveys were conducted to validate model predictions.

**Validation of a Remote Sensing Model**

WorldView-3 sensor data was employed to image Nginyang, Baringo County, Kenya, a divisional administration headquarters town for the county, and Nginyang River, which is adjacent to the town; the chosen site for validating pre-existing remote sensing model. Locational traits that made this study site ideal were initial spatial surveys that the river is seasonal and drained by Churtuten, Karuwon, and Cheptokokwo, including small streams. The river also serves nearby Nginyang town residents, and the Pokot nomadic pastoralist community, which depend on its water for domestic usage and watering of livestock. Spatial surveys provided contingency on the inspection of the existing remote sensing data that the imaged sites, which spanned the riverbed, were putative anthropogenic boreholes. Identified sites were then geolocated and their spatial reference along the riverbed projected into Universal Transverse Mercator (UTM) Zone 36N. Spectral signatures obtained from the pre-existing remote sensing data of a known, productive *Anopheles* borehole habitat in the Chemolingot study site was then employed to identify signatures representing anthropogenic boreholes from the remote sensing data in Nginyang site.

Validation of model predictions were carried out by a ground-based team of two entomologists who trekked along the 5 km course of the Nginyang River (*Image 7*). Riverbed surveys of all forecasted boreholes were accomplished by the team’s visit to all sites predicted to
contain anthropogenic boreholes by the remote sensing model, including sites that may have been missed by the signature model. A count for all identified anthropogenic boreholes that were predicted by the signature model, and positive for horizontally lying *Anopheles* vector mosquito larvae was then obtained.

*Figure 7:* Cartographic representation of the Nginyang study site.
CHAPTER THREE:

RESULTS

In the initial ground-based survey of boreholes at the Chemolingot study site, a total of 243 boreholes were inspected for aqua-terrestrial, horizontally lying Anopheles larvae. The results from this survey are shown in Table 1. Also, the projected GPS coordinates from all sampled boreholes that were georeferenced in ArcGIS, are displayed in Figure 8.

Table 1: Number of anthropogenic boreholes surveyed bi-weekly from January 2015 to June 2015 for Anopheles vector mosquito larvae. Results from observed presence or absence of larvae, are also shown

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Sampled Boreholes</th>
<th>Larvae Present (1)</th>
<th>Larvae Absent (0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Churtuten</td>
<td>84</td>
<td>43</td>
<td>41</td>
</tr>
<tr>
<td>Cheptokokwo</td>
<td>94</td>
<td>50</td>
<td>44</td>
</tr>
<tr>
<td>Karuwon</td>
<td>65</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>243</td>
<td>124</td>
<td>119</td>
</tr>
</tbody>
</table>
Figure 8: GPS points of all surveyed boreholes in the study site at Chemolingot georeferenced and overlaid onto WorldView-3 sensor data in ArcGIS.
Table 2 show the radiometric/spectral signature values obtained from a georeferenced, productive *Anopheles* borehole habitat in Karuwon River (latitude 0.9883° North and longitude 36.00° East).

**Table 2:** Radiometric/spectral signature values obtained from the remotely sensed WorldView-3 (0.30-meter panchromatic resolution) visible and near infra-red waveband data. The values were generated from a productive habitat; in terms of availability of *Anopheles* larvae throughout the sampling period in Chemolingot study site.

<table>
<thead>
<tr>
<th>Band Wavelength (nm)</th>
<th>Source Band Index</th>
<th>Radiometric/Spectral Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red (630 - 690)</td>
<td>5</td>
<td>348</td>
</tr>
<tr>
<td>Green (510 – 580)</td>
<td>3</td>
<td>345</td>
</tr>
<tr>
<td>Blue (450 - 510)</td>
<td>2</td>
<td>255</td>
</tr>
<tr>
<td>Infrared_1(770 - 895)</td>
<td>7</td>
<td>420</td>
</tr>
</tbody>
</table>

The probability indicator prediction for productive boreholes at the study site in Chemolingot shown in **Figure 9**, optimally identified boreholes that likely exceeded the primary/critical threshold for productivity of *Anopheles* mosquito vector larvae. In the outputted results described by the legend, a probability of 1 was geospatially assigned to boreholes that exceeded the threshold, and 0 was assigned to boreholes below the threshold. Results from the probability model showed that 193 boreholes exceeded the threshold for *Anopheles* vector mosquitoes productivity.
Figure 9: Probability indicator prediction for productive boreholes at the study site in Chemolingot.
Results from the employment of a remote sensing model to identify anthropogenic boreholes in Nginyang riverbed, and “ground-truthing” survey of model predictions, are shown by the following tables and figures.

Figure 10: Putative anthropogenic boreholes that were predicted by the existing WorldView-3 sensor data in the Nginyang riverbed site.
Figure 11: Outputted probability model that was developed to identify signatures representing boreholes from remote sensing data in Nginyang riverbed. Productive boreholes were also predicted.
Table 3: Model predictions for boreholes in the Nginyang riverbed site.

<table>
<thead>
<tr>
<th>Rivers (Nginyang)</th>
<th>Predicted Boreholes</th>
<th>Productive Boreholes (indicator threshold)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>

Table 4: Results from ground-based survey of model predictions for boreholes in the Nginyang riverbed site.

<table>
<thead>
<tr>
<th>Rivers (Nginyang)</th>
<th>“Ground-truthing” Total Boreholes</th>
<th>Positively Predicted Boreholes</th>
<th>False Positives (Specificity)</th>
<th>False Negatives (Sensitivity)</th>
<th>Presence of Larvae in Predicted Boreholes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27</td>
<td>22</td>
<td>3/25</td>
<td>5/27</td>
<td>17/22</td>
</tr>
</tbody>
</table>

A total of 25 putative borehole sites in the stretch of the Nginyang riverbed chosen for the “ground-truthing” validation were predicted by the remote sensing model. Upon ground-based survey of model predictions on the entire 5 kilometer course of the riverbed, 27 boreholes were identified. Of these, 22/25 predicted sites were validated as anthropogenic boreholes while 3/25 sites were observed to be ground depressions and therefore not classified as anthropogenic boreholes. In contrast, 5 boreholes not predicted by the signature model were found. Therefore, results from this study suggested that the remote sensing model exhibited a sensitivity of approximately 82% (22/27 boreholes seen in the “ground-truthing” validation were correctly predicted) and specificity of 88% (22/25 of the predicted boreholes were confirmed by the “ground-truthing” validation).
CHAPTER FOUR: DISCUSSION

Results from this study suggest that the spectral signature obtained from remote sensing data of a known productive *Anopheles* borehole habitat in Karuwon River site, optimally identified signatures representing anthropogenic boreholes from remote sensing data employed in Nginyang riverbed with high degree of accuracy (sensitivity of 82% and specificity of 88%). The remote sensing model described herein will be extremely useful in precisely mapping of dry-season malaria transmission foci in sub-Saharan Africa, and other endemic riverine in tropical climates, where anthropogenic borehole habitats are available and contain the signature. Boreholes in both sites were stable for most part of the six-month period of survey, especially days into the short rainy season in April and May; however, when the dry season progressed from January to April, they began to shrink/dry, leaving some permanent boreholes active; typically, those with underlying bedrock and sandy soils, which provided for low percolation rate, longer residence time, and year to year habitat stability.

Surveys in Churtuten, Karuwon, and Cheptokokwo Rivers, including “ground-truthing” study conducted to assess model’s precision based on sensitivity and specificity tests in Nginyang riverbed, determined that anthropogenic boreholes were a significant source of dry season vector mosquitoes. This study, however, does not independently confirm that anthropogenic boreholes were the exclusive refuge habitat for *Anopheles* vector mosquitoes during the dry season, since other potential habitats observed in both study sites (e.g., water tanks, shallow vernal pools and
ditches), could be contributing to malaria endemicity. Shallow vernal pools and ditches occurred during the rainy season, while water tanks, which were used to store large volume of water, were located in some residences, and inside both towns. Studies conducted by Amerasinghe et al., (2001) on small irrigation tanks as source of malaria vector mosquitoes in North-Central Sri Lanka, showed that major Anopheles vectors of malaria in Sri Lanka occurred infrequently in tanks; however, important secondary vectors and others that were involved in malaria transmission did occur frequently.

Because the signature composition for borehole habitats was mostly sandy soils and water, and since the images were taken on January 12, 2015 (dry season), while “ground-truthing” investigations were conducted after conclusion of the six-month borehole survey in June (following the short rainy period in April and May); it was possible that model’s accuracy was affected by rain which may have led to disappearance/shrinking of anthropogenic boreholes. Indeed, upon “ground-truthing” survey, the habitats were no longer contained in the existing remote sensing images, and were classified as ground-depressions. This suggests that the remote sensing model may be most accurate when used to analyze images taken during the dry-season. Shrinking/disappearance of borehole habitats was a limiting factor, which may have resulted in re-sampling of coincidental borehole habitats surveyed for the presence of aqua-terrestrial, horizontally lying Anopheles larvae (124/243 – 51% in Chemolingot site, and 17/22 – 77% in Nginyang site). This in turn may have affected model’s prediction for boreholes that actually contain larvae in Nginyang riverbed (24/25 – 96%).

Since borehole identifications were based upon high resolution WorldView-3 images (0.31 meter), which provided for an optimal, predictive, remote sensing model, the signature can be generalizable to the tropical savanna riverine only, where the collection of reliable habitat related
covariates (e.g., habitat size, distance to human habitation etc.) over large geographical areas is unattainable, and anthropogenic boreholes are available. Precise mapping of *Anopheles* vector mosquito’s geo-locations in war-torn sub-Saharan countries such as South Sudan, Central African Republic, and the Democratic Republic of the Congo, which continue to suffer from unstable governments and lack of infrastructure, would benefit from targeted, and sustainable mosquito larval control in endemic foci. The current cost of WorldView-3 sensor data ($20 USD per km²) makes it too expensive to be widely deployed for identifying anthropogenic borehole habitats on a large scale area, especially for sub-Saharan countries, which are under economic constraints. However, the cost of these images can be reduced by limiting the acquired imagery for use, for example, Panchromatic ($14.50 USD per km²) bands can be purchased instead of the 8-Band Panchromatic and Multispectral Bundle ($20 USD per km²). Alternatively, the WorldView-3 sensor images can be clipped to rivers and streams features using the ArcGIS geoprocessing clip tool making it cost-effective and suitable for intended study. Also, freely downloadable sensor data can be processed further by radiometrically correcting pixel for accuracy, although calibration and validation does not improve imagery resolution.

The remote sensing model from this study may be employed to implement an integrated vector management (IVM) program for targeted sustainable larval control with limited resources. According to Gu & Novak (2005); Mittal (2003), countries with endemic malaria will benefit from renewed malaria eradication programs (i.e. Integrated Vector Management), which rely heavily on the management of larval habitats and the application of environmentally friendly and powerful microbial insecticides, such as *Bacillus thuringiensis israeliensis* (Bti). Favorably, the distinct ecological features found in tropical savanna climate, such as lengthy dry period with very little precipitation, makes larval control a more feasible tool than in wet tropical climate, tropical
monsoon climate, or other malaria endemic zones in the tropics, where annual precipitation averages are higher; therefore, if focal sites the vector mosquitoes inhabit during the dry season can be identified, and managed, then the reservoir of vector species that “seed” exploding populations at the onset of the rain season can be eliminated (Fillinger et al., 2004).

In conclusion, the application of WorldView-3 sensor data to remotely identify anthropogenic boreholes in dry riverbeds of tropical savanna ecosystem, and to obtain a spectral signature model from a positively sampled *Anopheles* habitat contained in the remote sensing data, is significant in sub-Sahara’s dry-land ecology studies of malaria. Results from this study suggested that a remote sensing model based upon a productive borehole habitat, optimally predicted the locations of unknown boreholes in dry-riverbed with high degree of accuracy. Future studies should examine how the signature model may be employed to implement an integrated vector management program targeting seasonally productive anthropogenic boreholes. Also, the role of water tanks as source of malaria vectors in tropical savanna ecosystem should be examined, since these could represent a perennial source of *Anopheles* mosquitoes.
REFERENCES


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James Pkemoi Kukat was born in Kapedo, Baringo County, Kenya and earned his Bachelors of Science in Environmental Health Sciences at Western Carolina University. He has also earned minors is Chemistry at Western Carolina University. He is continuing his education by pursuing a Master’s of Science in Public Health - Global Communicable Diseases at the University of South Florida. While finishing his degree, he has also earned graduate certificates in global health practice, and applied biostatistics.