Prevention of malaria transmission around reservoirs: an observational and modelling study on the effect of wind direction and village location

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Open Access Published: September, 2018 DOI: https://doi.org/10.1016/S2542-5196(18)30175-X

Summary

Background

Many large dams are constructed annually in Africa, with associated reservoirs that might exacerbate the risk of malaria in new villages built nearby. We aimed to investigate the heterogeneous risk of malaria around reservoirs related to the impact of wind direction on malaria transmission.

Methods

Between June 15, 2012, and April 22, 2015, we obtained field data on climate and hydrological conditions, and monitored *Anopheles* mosquito populations around the Koka reservoir in Ethiopia using in-situ weather stations, mosquito light traps, and larval dipping. The field data were used to calibrate a field-tested, spatially explicit mechanistic malaria transmission model, the Hydrology, Entomology, and Malaria Transmission Simulator (HYDREMATS), to investigate the effect of relative wind direction on malaria transmission and associated mechanisms. We combined our simulation results and observational data to assess the association between village location around a reservoir and risk of malaria.

Findings

HYDREMATS simulations showed that wind blowing from a village towards a reservoir increases the size of malaria vector populations, whereas wind blowing from a reservoir towards a village decreases the size of malaria vector populations, which was consistent with our field data. Larval mortality is low in locations with village-to-reservoir wind due to weak surface waves, and this wind direction creates conditions that enable mosquitoes to identify village locations more easily than in conditions caused by reservoir-to-village wind, which increases the size of malaria vector populations, and thus malaria transmission. Among the wind conditions investigated (0·5–5 m/s), the effect of CO_2 attraction on the size of the *Anopheles* population was largest at wind speeds of 0·5 m/s and 1 m/s, decreasing with higher wind speed. At a wind speed of 5 m/s, the effect of CO_2 attraction was negligible, whereas the effect of waves was strongest. The effect of advection on *Anopheles*population size was negligible at all wind speeds and wind directions.

Interpretation

The effect of wind on malaria transmission around reservoirs can be substantial. The transmission of malaria can be minimised if the location of villages situated near a reservoir is carefully considered. For areas in which the environmental conditions surrounding a resevoir are equal, villages should be located downwind of reservoirs to reduce the incidence of malaria, although further research will be required in locations where wind direction changes in different seasons.

Funding

US National Science Foundation, and Cooperative Agreement between the Masdar Institute of Science and Technology, Abu Dhabi, UAE, and the Massachusetts Institute of Technology, Cambridge, MA, USA.

Introduction

Although scientific advances have led to the development of interventions to control malaria transmission, human behaviour has also contributed to malaria endemicity. Climate change might potentially enhance malaria transmission.[1,2] Environmental modifications, such as the construction of dams and formation of irrigated fields, can also increase malaria transmission.[3,4,5,6, [7,8,9] The construction of new dams is unlikely to be stopped because of concerns about public health issues, such as malaria. Annually, an estimated 160–320 new large dams are constructed worldwide, a high percentage of which are located in African countries. These projects often require the construction of resettlement villages.

Although the proximity of villages to reservoirs is a well known risk factor for malaria transmission,[7] the effect of village location relative to reservoir location and wind direction is poorly understood. With the exception of small-scale laboratory experiments,[10,11,12,13] a small number of field studies[14,15,16,17] have indicated that village location and wind direction affect malaria transmission. Midega and colleagues[14] reported that malaria risk in the Kilifi district in Kenya is determined by proximity to larval sites and by wind direction. Studies[16,17] from the Gilgel-Gibe reservoir in Ethiopia found that malaria incidence did not correlate with distance from the reservoir, which contradicts previous literature,[7] and reported that malaria incidence is markedly higher in villages located in the south of the reservoir than the north.

Research in context

Evidence before this study

We searched PubMed from database inception until April 30, 2017, without language restrictions, using the search terms ("malaria" OR "Anopheles") AND ("dam" OR "reservoir" OR "location" OR "wind direction" OR "hotspots"). Numerous studies have reported an association between proximity to dams (ie, distance) and malaria transmission. However, only seven studies have investigated the two-dimensional spatial impact (ie, distance and direction) around dams, among which only three studies explicitly included wind direction as a contributing factor in malaria transmission. By contrast, field and laboratory experiments have provided substantial evidence that wind influences the behaviour of *Anopheles* mosquitoes.

Added value of this study

This study shows that wind direction and wind speed affect malaria transmission, and highlights that this is an important factor to consider when selecting the location of resettlement villages around dams and reservoirs. We used observational data and a detailed mechanistic model that was tailored to, and tested for, reservoir environments, which increases confidence in the results of this study. This study provides observational and simulational evidence that village location and relative wind direction are important factors in determining malaria transmission potential around reservoirs.

Implications of all the available evidence

In addition to climatic factors, the location of villages influences the risk of malaria transmission around reservoirs. The direction that villages are situated at with respect to reservoirs influences malaria transmission through modulation of the behaviours of *Anopheles* mosquitoes. Individuals who live in villages located downwind of reservoirs are less likely to contract malaria than individuals who live in villages that are located upwind of reservoirs. The results of this study provide a policy guideline for selecting the location of resettlement villages around dams and reservoirs. For areas in which the environmental conditions surrounding a resevoir are equal, villages should be located downwind of reservoirs to minimise malaria transmission.

Wind influences the behaviour of *Anopheles* mosquitoes and hence malaria transmission via three mechanisms: aquatic-stage mortality caused by high waves, advection of adult mosquitoes, and efficient host-seeking activity through CO_2 attraction.

[18] To the best of our knowledge, the Hydrology, Entomology, and Malaria Transmission Simulator (HYDREMATS)[18,19] is the only mechanistic malaria transmission model that incorporates the impact of wind on the behaviour of *Anopheles* mosquitoes.

In this study, we investigate the effect of wind direction on malaria transmission around a reservoir using observational data and simulation data generated by the mechanistic malaria transmission simulator, HYDREMATS.[20]

Methods

Study location and data collection

This study was done at Ejersa-Dungugi-Bakele kabele, a village near the Koka Reservoir in Ethiopia with a population of 2900 people (figure 1), which is located in the Ethiopian Rift Valley. Ejersa is located northwest of the Koka Reservoir with an elevation of approximately 1600 m and mean annual temperature of around 21·1°C. Between 2009 and 2014, the annual incidence of malaria in the village was 55 cases per 1000 individuals. In this area, approximately two-thirds of malaria infections are caused by *Plasmodium falciparum* and one-third by *Plasmodium vivax*. The most common malaria vectors present at Ejersa are *Anopheles arabiensis*, *Anopheles funestus*, *Anopheles pharoensis*, and *Anopheles coustani*.[7] Malaria is hypoendemic in this area, and the incidence is declining as a result of control measures. In Ejersa, the reservoir shoreline, marginal pools beside the shoreline, and puddles caused by rain are major breeding sites for *Anopheles*mosquitoes.[7,20] Marginal pools and puddles caused by rain are the main breeding sites for *A arabiensis*, the most competent vector for malaria transmission in the area, whereas *A funestus*, which is a less competent vector for malaria transmission than *A arabiensis*, mainly breeds at reservoir shorelines. The three types of breeding sites are simulated in HYDREMATS, of which, only the resevoir shoreline is affected by waves.

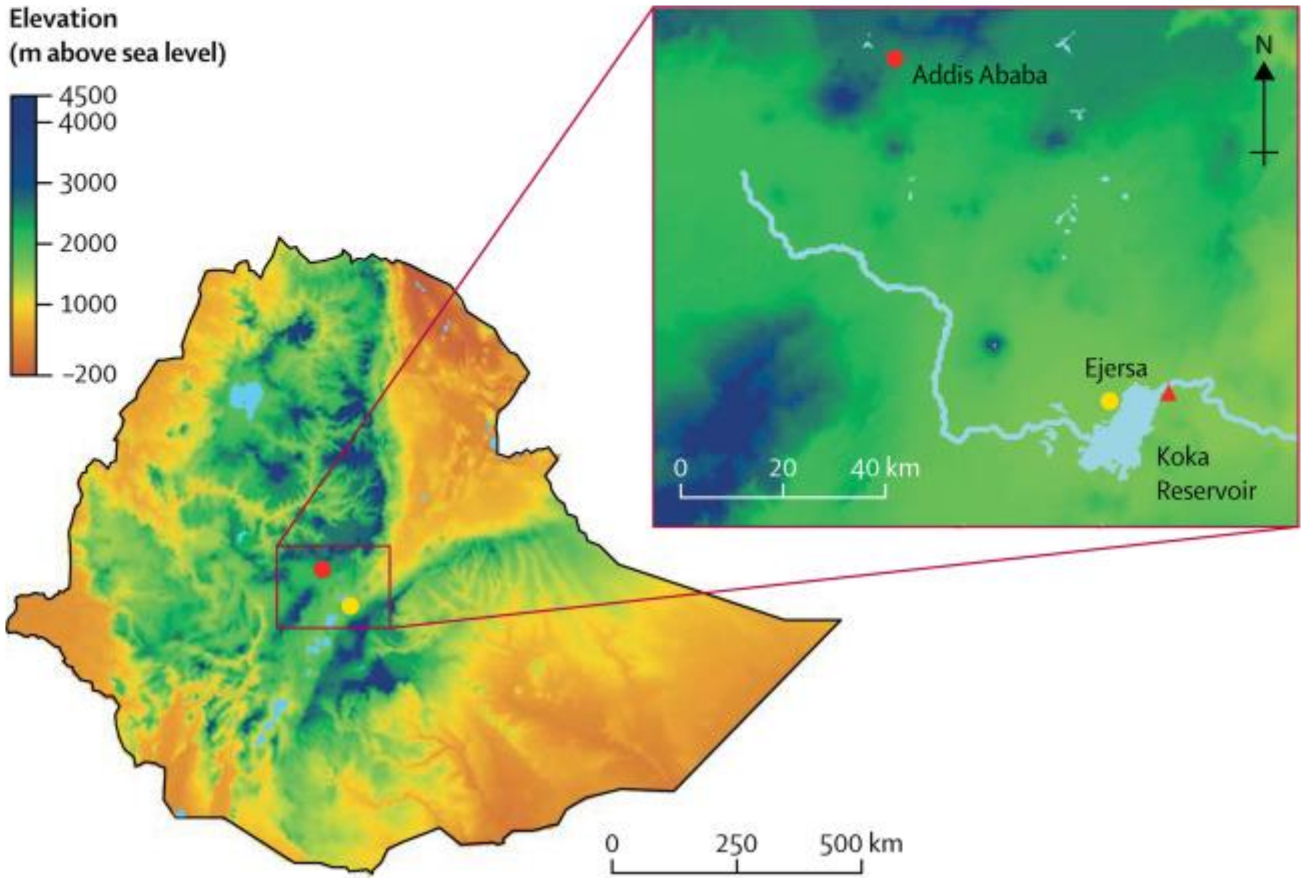

Figure 1Location of study site

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We collected environmental data and *Anopheles* population data between June 15, 2012, and April 22, 2015, around the Koka Reservoir.[20] We collected detailed data using in-situ weather stations, mosquito light traps, and larval dipping. Climatic data, including temperature, relative humidity, rainfall, solar radiation, wind speed, and wind direction, were obtained from a weather station every 30 min. Hydrological conditions (ie, soil moisture and groundwater surface level) were also monitored at two locations in the village. Daily water levels of the Koka Reservoir were obtained from the Ethiopian Electric Power Corporation (Addis Ababa, Ethiopia) and a high-resolution (8 m) digital elevation model from Apollo Mapping (Boulder, CO, USA). We monitored *Anopheles*mosquito populations using six light traps and larval dipping every 1–2 weeks. The mosquitoes captured were classified at the genus level (ie, *Anopheles* or *Culex*) and *Anopheles* mosquitoes were further classified by sex. Data on malaria incidence were obtained from local clinics in Ejersa. Detailed information about the collection of field data is shown in the appendix.

Relative wind direction and village location

The location of a village and wind direction were defined using a polar coordinate with origin at the centre of a reservoir (figure 2). The absolute location of a village (θv) and the wind direction (θw) are measured clockwise relative to the north. The wind direction relative to the village location (relative wind direction) is defined as:

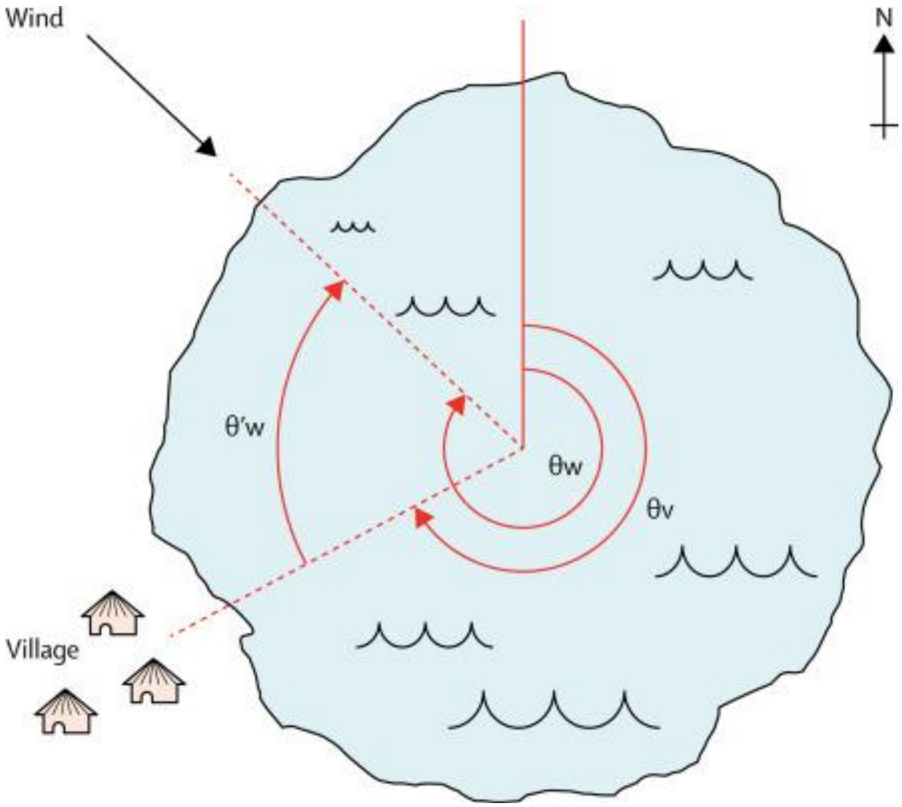

Figure 2Definition of wind direction

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$$\theta'w = \theta w - \theta v$$

Malaria transmission model

We used the HYDREMATS,[18,19,20] the most detailed mechanistic malaria transmission model,[21] to simulate environmental conditions and behaviours of *Anopheles* mosquitoes in space and time. The model has been used previously[22]

[,23,24] to analyse the effect of environmental perturbation on malaria transmission.

HYDREMATS has been extended to simulate malaria transmission around reservoirs incorporating the effect of wind.[18,20] The details of the *Anopheles* mosquitoes' flight behaviours that are influenced by wind were included in the model on the basis of mosquito physiology and the physical dispersion process of CO_2 plumes,[18] in addition to the effect of advection.[19] The effect of wind-induced waves on larval mortality was also incorporated in the model.[18]

Before this study, the HYDREMATS was calibrated using field observations of the *Anopheles* mosquito population, malaria incidence, and hydrological conditions in Ejersa (HYDREMATS Ejersa model;[20] appendix). HYDREMATS is built entirely on physically or biologically valid model equations, rather than regression models to fit observed variables. Thus, noticeable discrepancies were identified between some simulations and field observations (eg, soil moisture at deeper levels, and malaria incidence between late 2013 and early 2014), but these were deemed to be within a reasonable range.[20] HYDREMATS does not have a representation of multiple species of *Anopheles*. In this study, the same simulation period as in the previous study[20] (Jan 1, 2012–Dec 31, 2014) was applied.

Effects of wind direction and wind speed

We investigated the effects of wind direction in the HYDREMATS Ejersa model using prescribed wind conditions instead of observed conditions. Simulation experiments were done by applying different fixed wind directions and fixed wind speeds throughout the simulation period of 3 years (fixed all models). All other environmental conditions were kept the same as observed in Ejersa to enable the effects of wind direction and wind speed to be analysed independently from other environmental factors. The fixed wind speeds (u) used were u= 0·5, 1, 2, and 5 m/s. The fixed wind directions (relative wind directions) were θ'w= 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°. The experiments with θ'w=0° and 360° were identical. For comparison, we did an additional experiment at each wind speed, applying random wind directions throughout the simulation period (random model). Each simulation experiment consisted of five simulations using the same environmental conditions, but with different seed numbers to reduce the stochastic variability in malaria transmission simulations.

Wind mainly influences the behaviours of *Anopheles* mosquitoes through the following three mechanisms: wind-induced surface waves, advection of adult mosquitoes, and attraction of adult mosquitoes via dispersion of CO_2 (ie, CO_2 attraction).
[18]

The fixed all model and the random model applied fixed wind directions and random wind directions, respectively, to the three mechanisms that affect *Anopheles* mosquito behaviour. To identify the dominant mechanisms in different wind conditions, we did an additional three sets of experiments for each wind direction and wind speed (table). In the additional simulations, fixed wind direction was applied to affect only one of the three mechanisms (waves, advection, or CO_2attraction) in the fixed wave, fixed advection, or fixed CO_2 attraction models. Random wind direction was applied to the other two mechanisms.

TableExperimental HYDREMATS models used to investigate the effects of wind

	Wind direction affecting waves	Wind direction affecting advection	Wind direction affecting CO_2attraction
Fixed all	Fixed	Fixed	Fixed
Random	Random	Random	Random
Fixed wave	Fixed	Random	Random
Fixed advection	Random	Fixed	Random
Fixed CO_2attraction	Random	Random	Fixed

The fixed all model applies fixed wind directions and the random model applies random wind directions to the three mechanisms through which wind direction influences malaria transmission. In the fixed wave, fixed advection, and fixed CO_2 attraction models, fixed wind direction only affects the mechanisms of waves, advection, and CO_2 attraction, respectively. For the other mechanisms, random wind direction was used.

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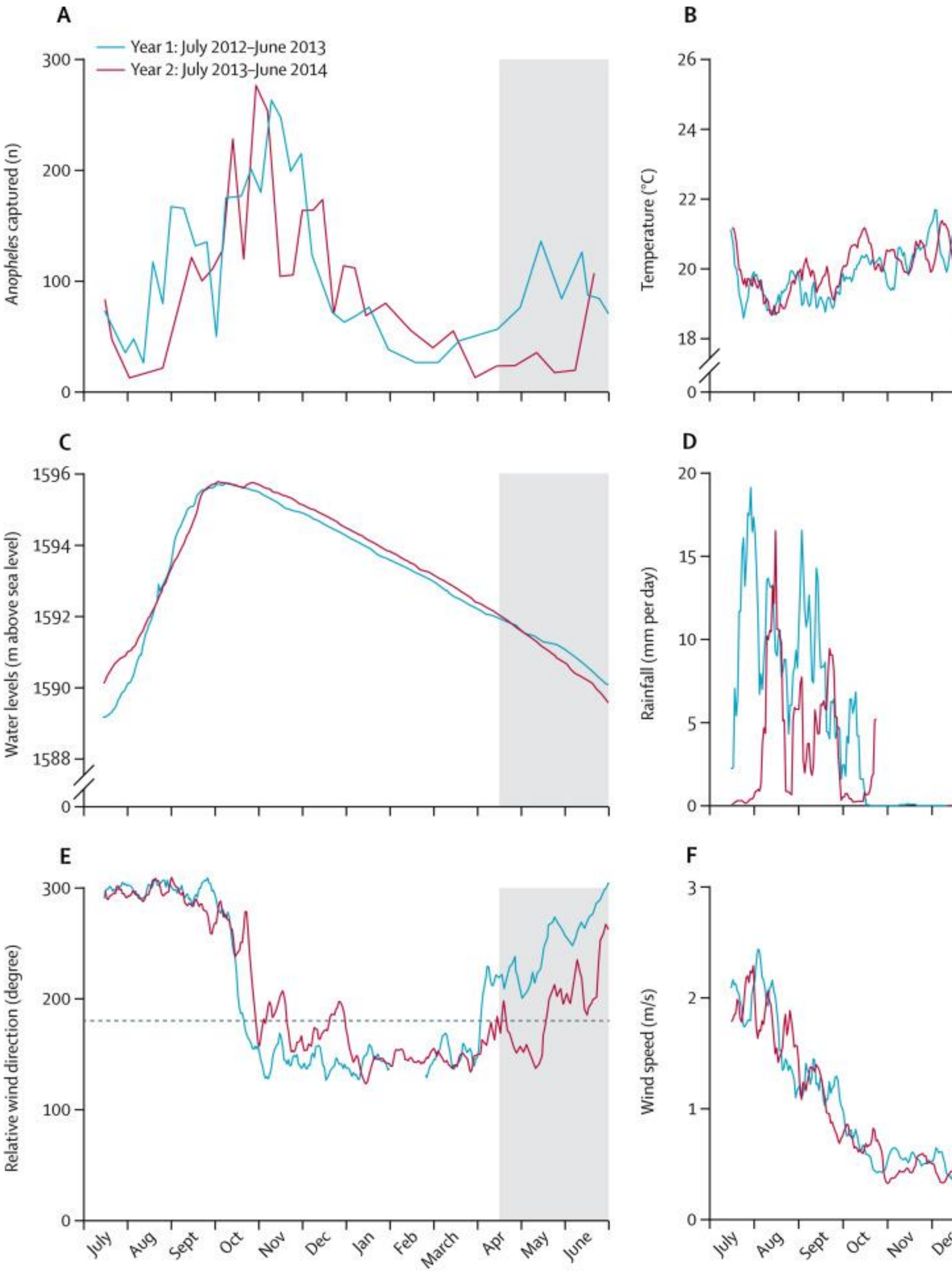
Role of the funding source

The funders of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the manuscript. The corresponding authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Ejersa has two *Anopheles* seasons: the major *Anopheles* season (between September and December) and the minor *Anopheles*season (between April and June; figure 3A). During year 1 of field observation (July 2012–June 2013), the *Anopheles* population was markedly higher between April and June than in year 2 of field observation (July 2013–June 2014; figure 3A): the average number of *Anopheles* captured per night was 105 in year 1 compared with 24 in year 2. The difference in the number of *Anopheles* mosquitoes between year 1 and 2 during the major *Anopheles* season was small.



A
Year 1: July 2012–June 2013
Year 2: July 2013–June 2014
Anopheles captured (n)
300
200
100
0
B
Temperature (°C)
26
24
22
20
18
0
C
Water levels (m above sea level)
1596
1594
1592
1590
1588
0
D
Rainfall (mm per day)
20
15
10
5
0
E
Relative wind direction (degree)
300
200
100
0
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
March
Apr
May
June
F
Wind speed (m/s)
3
2
1
0
July
Aug
Sept
Oct
Nov

Figure 3Observed environmental conditions and *Anopheles* populations in Ejersa
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Between April and June, the average temperature was 23·3°C in year 1 and 23·8°C in year 2 (figure 3B). During the same period, the average reservoir water levels were 1591·3 m above sea level with an average recession rate of 2·3 cm per day in year 1, compared with average reservoir water levels of 1591·2 m above sea level and an average recession rate of 3·0 cm per day in year 2 (figure 3C).

Other climatic conditions observed are shown in figures 3D–F. During the minor mosquito season, rainfall was low (14 mm per month in year 1; 36 mm per month in year 2; figure 3D). The difference in relative humidity between year 1 and year 2 was small (55% in year 1 *vs* 50% in year 2). Wind direction and wind speed were markedly different during the minor *Anopheles* season in years 1 and 2 (figures 3E, 3F). In year 1, the average wind speed (1·09 m/s) was almost twice as high as that in year 2 (0·57 m/s), and the average wind direction differed by nearly 60° (relative wind direction 238° in year 1 *vs* 181° in year 2).

The fixed model simulations with village-to-resevoir wind (θ'_w=0° or 360°) resulted in a larger *Anopheles* population (figure 4A) and a higher relative number of malaria infections (figure 4B) than the random model. Fixed model simulations with reservoir-to-village wind (θ'_w=180°) resulted in a smaller *Anopheles* population (figure 4A) and a lower relative number of malaria infections (figure 4B) than the random model. The increase in *Anopheles* population size was larger with village-to-reservoir wind (eg, >4 times larger at θ'_w=0° or 360° than random wind direction at a wind speed of 1 m/s) than the decrease in *Anopheles* population observed with reservoir-to-village wind (eg, <2 times smaller at θ'_w=180° than with random wind direction at a wind speed of 1 m/s). The simulated effects of wind direction and wind speed were found to have a larger effect on malaria transmission than on the size of the *Anopheles* population.

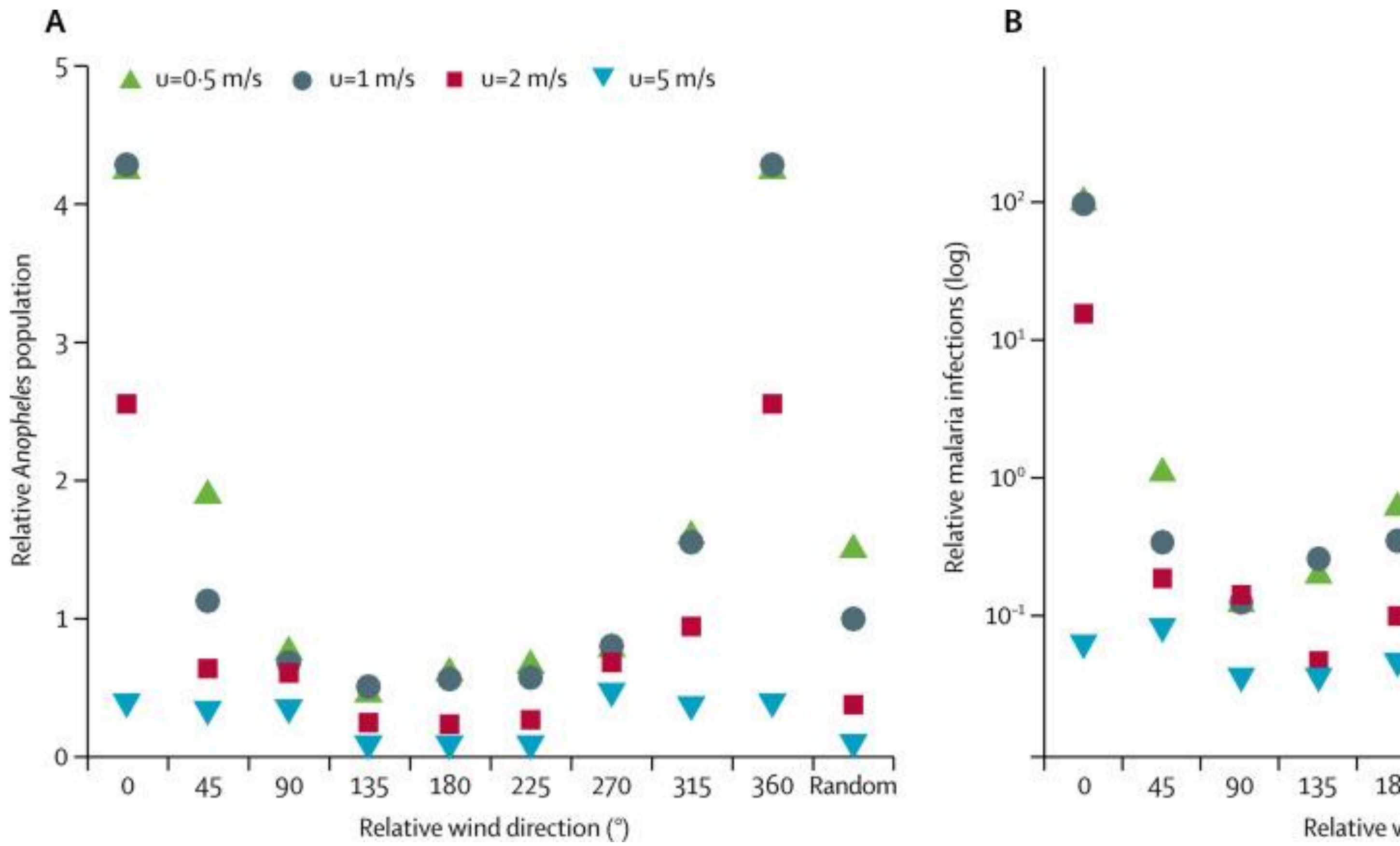

Figure 4Effects of wind direction and wind speed on the *Anopheles* population (A) and malaria transmission (B)

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The magnitude of the impact of wind direction was dependent on wind speed. Slower wind speed resulted in larger *Anopheles*populations (figure 4A) and a higher number of malaria infections (figure 4B) than faster wind speeds. The effect of wind speed was apparent at wind speeds 1 m/s, 2 m/s, and 5 m/s, but not between 0·5 m/s and 1 m/s. Compared with the model with random wind direction at a wind speed of 1 m/s, the increase in *Anopheles*population size with village-to-reservoir wind (θ'w=0° or 360°) was larger at wind speeds of 0·5 m/s and 1 m/s than at 2 m/s and 5 m/s. The decrease in *Anopheles* population size with reservoir-to-village wind (θ'w=180°) was larger at wind speeds of 2 m/s and 5 m/s than at 0·5 m/s and 1 m/s.

At wind speeds of 0·5 m/s and 1 m/s, the mechanism of CO_2attraction has the largest effect on the size of the *Anopheles*population; the results from the fixed CO_2 attraction model were similar to those from the fixed all model, whereas the results from the fixed wave and fixed advection models were similar to the random model (relative *Anopheles* population of approximately one; figure 5). At a wind speed of 2 m/s, the effect of CO_2 attraction on *Anopheles* population size was smaller, whereas the effect of waves was larger than at a wind speed of 0·5 m/s and 1 m/s. At a wind speed of 5 m/s, the effect of waves was the strongest, and the effect of CO_2 attraction was negligible. The contribution of advection was also negligible at all wind speeds and wind directions (figure 5).

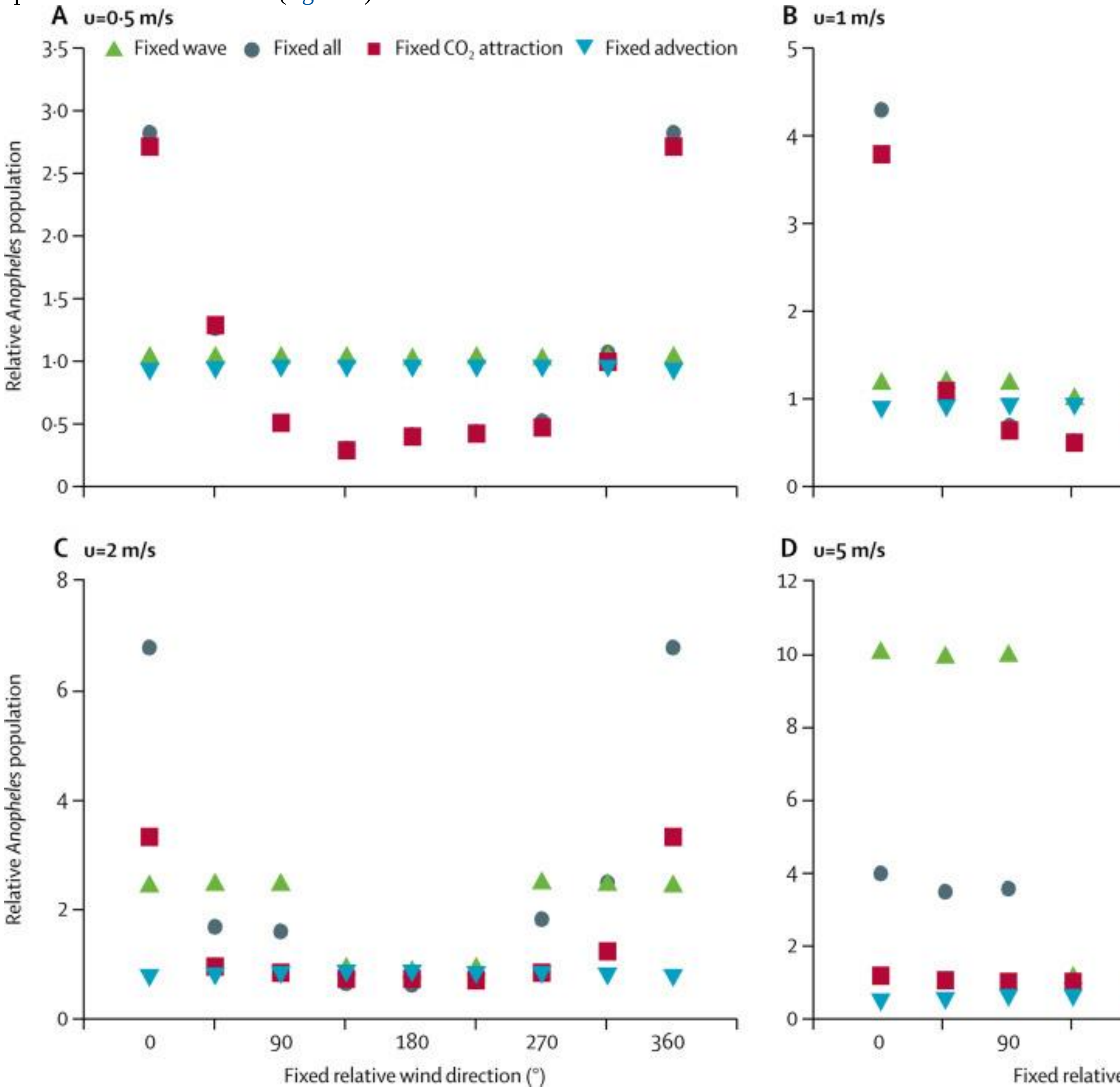

Figure 5Relative *Anopheles* population size at different wind direction and wind speeds simulated by the HYDREMATS model

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Discussion

Wind is rarely considered an important factor that influences malaria transmission; however, the results of this study show that it can substantially influence the risk of malaria around a reservoir. Although the local climate cannot be controlled, the location of villages around reservoirs can be selected on the basis of relative wind direction using the observed wind profile. Wind affects the dynamics of the *Anopheles* mosquito population and malaria transmission via two mechanisms: larval mortality due to waves and efficiency of host-seeking through CO_2 attraction. In areas where there is village-to-reservoir wind, larval mortality is low because waves are weak and *Anopheles* can find hosts efficiently as a result of strong CO_2 attraction, both of which increase the size of the *Anopheles* population (figure 6). Thus, people who live in villages upwind of a reservoir are expected to have larger risk of malaria than people who live in villages located downwind of a reservoir. Individuals residing in villages located parallel to the wind direction are likely to have an intermediate risk of malaria. Wind direction varies throughout the year, thus further analysis is needed to assess the potential risk of malaria transmission when choosing the location of resettlement villages. This study provides a policy guideline for selecting village locations during dam construction.

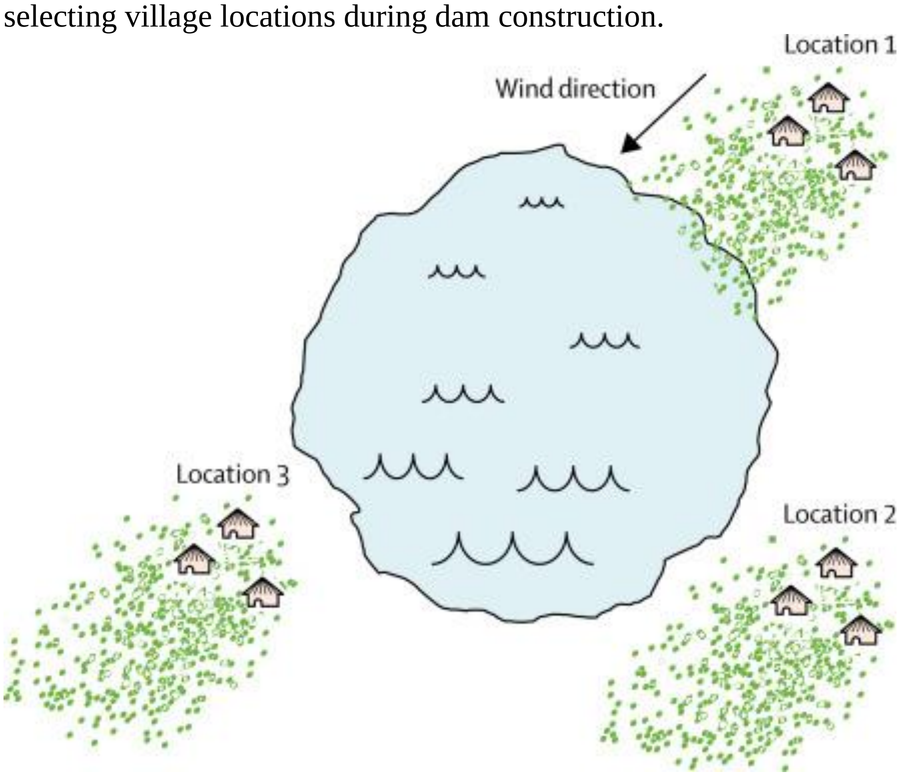

Figure 6Schematic of the role of wind for different village locations
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Wind affects the dynamics of the *Anopheles* population by influencing wave activity, advection of adult mosquitoes, and CO_2attraction.[18] The influence of these three mechanisms on the size of the *Anopheles* population is dependent on wind direction and speed. Out study showed that at a low wind speed, the *Anopheles*population dynamics were predominantly influenced by the mechanism of CO_2 attraction. As wind speed increases, the effect of CO_2 attraction became smaller. At wind speeds of more than 2 m/s, the effect of waves outweighed that of CO_2 attraction. The effect of advection was marginal at all wind speeds and wind directions. Generally, village-to-reservoir wind from $\theta'w=0°$ increased the size of the *Anopheles* population, and reservoir-to-village wind from the *Anopheles* population $\theta'w=180°$ decreased the size of the *Anopheles*population.

The effect of waves on the *Anopheles* population was stronger at higher wind speeds and with a relative wind direction of 180°. Aquatic mortality increased with larger waves, which can be caused by higher wind speeds and larger fetch. Fetch is zero when $\cos(\theta'w)$ is 0 or higher and increases with $|\cos(\theta'w)|$ when $\cos(\theta'w)$ is less than 0. The largest fetch occurs at $\theta'w=180°$. The wave effect can be attenuated by topographical features or vegetation at the shoreline. The mortality of aquatic-stage mosquitoes caused by high waves is unique to large water bodies (eg, reservoirs). The effect of wind-induced waves on the *Anopheles* population size is expected to be higher in locations near large areas of deep water than small areas of shallow water.

The effect of CO_2 attraction is large at low wind speeds because CO_2plumes travel further at a low wind speed, maintaining a high CO_2concentration. Above a certain concentration of CO_2 (ie, 40 ppm higher than ambient concentration[18]), *Anopheles* mosquitoes detect the presence of human settlements upwind and fly towards them with partial directed flight (mosquitoes' flight is simulated as a combination of random flight and directed flight). Below this threshold concentration, *Anopheles* fly randomly with an assumed directed flight component of zero. The strength of the directed flight component depends on the concentration gradient of CO_2. The area in which *Anopheles* can sense elevated CO_2 concentrations decreases with higher wind speed,[18] limiting the effect of CO_2attraction on *Anopheles* population size. The effect of CO_2 attraction on *Anopheles* population size is assumed to be large around reservoirs because of the heterogeneous environment, where houses are located on one side of the shoreline breeding sites with a reservoir located on the other side.

The observed difference in *Anopheles* population size during the minor *Anopheles* season between year 1 and year 2 can be explained by wind direction. The minor *Anopheles* season is often associated with high temperature and the presence of marginal pools created near shorelines because of low reservoir water levels;[20] however, the similarity in these factors between year 1 and year 2 suggests that they cannot explain the observed differences in *Anopheles*population size.[25,26]

[,27,28] Other climatic conditions that might explain the observed difference in the *Anopheles* population were rainfall, humidity, wind direction, and wind speed. During the minor *Anopheles* season, rainfall was too low to affect the population dynamics of *Anopheles* in Ejersa.[20,29] The difference in relative humidity between year 1 and year 2 was also small, and thus was also unlikely to have caused the observed difference.[30] Wind direction and wind speed were markedly different during the minor *Anopheles* season in years 1 and 2. The relative wind direction during this season in year 2 was more similar to reservoir-to-village wind direction (θ'w=180°) than in year 1, which is consistent with our conclusion that reservoir-to-village wind creates unfavourable conditions for *Anopheles* populations. The observed wind speed during this season was also different between year 1 and year 2; however, our model suggested that a difference in wind speed of 0·5–1 m/s does not have a large effect on *Anopheles* population size.

The findings of a previous field study[17] around the Gilgel-Gibe reservoir in Ethiopia also support the conclusion of this study; high malaria incidence did not correlate with the proximity of the villages, but was found to cluster around the south of the reservoir. The dominant wind direction around this area is south-to-north wind (data from European Reanalysis Intrim[31]), which suggests that the risk of malaria is higher in locations south of the reservoir than north of the reservoir.

In conclusion, if all environmental conditions surrounding the resevoir are equal, the transmission of malaria can be minimised if resettlement villages are built downwind of reservoirs, rather than upwind, during the construction of dams and reservoirs. Future research should investigate the effect of seasonality on wind direction and other environmental factors that have a non-linear effect on *Anopheles* population dynamics and malaria transmission. Other factors that affect malaria transmission, such as proximity to a reservoir and to other villages, and economic factors, such as transport links, should be considered when the location of villages are chosen. More rigorous analysis on the importance of wind in malaria transmission and additional data obtained from field studies would further inform policy to prevent malaria transmission around reservoirs.

Contributors

NE and EABE conceived the study. NE conducted field studies and simulation studies. EABE supervised the research. NE wrote the manuscript. Both authors edited and approved the final manuscript.

Declaration of interests

We declare no conflicting interests.

Acknowledgments

We thank the Ethiopian researchers and students from Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, who through the Undergraduate Research Opportunities Program, provided substantial support during our field work. This work was supported by the US National Science Foundation (grant number EAR- 0946280) and by the Cooperative Agreement between the Masdar Institute of Science and Technology (Masdar Institute), Abu Dhabi, UAE and MIT.

Supplementary Material

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Supplementary appendix

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