# Of water and worms: Guinea worm re-emergence in Niger

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## ABSTRACT

This paper aims to provide a better understanding of the re-emergence of Guinea worm into the water bodies of the Tillabéri region of the Niger Sahel. It examines the period of re-emergence and subsequent decline from 2002 until 2006. Using a geographic information system combined with a statistical approach to examine the location data of lakes with Guinea worm-associated cases, it is shown that the locations of population centers with cases of Guinea worm disease, the locations of lakes infected with Guinea worm larva, and features of the built environment are correlated in space.

**Key words** | Africa, geographic information systems, Guinea worm

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## INTRODUCTION

*Dracunculus medinesis*, or Guinea worm as it is more commonly known, is a two-host nematode parasite affecting humans who drink water contaminated with Guinea worm larvae and is notable for its dramatic clinical manifestations. The number of cases of Guinea worm disease (dracunculiasis) has been in rapid decline since the early 1980s, when the Dracunculiasis Eradication Program (DEP) was formed and organized a coordinated worldwide eradication campaign (Cairncross *et al.* 2002). As the number of reported Guinea worm cases continues to decrease worldwide, the remaining regions in which it persists are those with the few remaining water bodies on the planet that are home to Guinea worm larvae. Since Guinea worm-infected individuals are the primary vector for transporting Guinea worm from water body to water body, the extent of Guinea worm spread is determined by the travel behavior of the few at-risk populations that live near Guinea worm-infected lakes. Much to the frustration of the DEP and the populations still living in regions infested with Guinea worm, there have been several resurgences of the parasite in the past decade: Chad, Mali, Niger, Ghana, and Ethiopia have all seen the total number of cases countrywide increase at some point during the past ten years (Callahan *et al.* 2013). If there is to be a resurgence of the parasite before full eradication has been achieved in other regions, it will inevitably stem from the human use of the few remaining infected water bodies.

This study tests the hypothesis that the distribution of features in the built environment relative to the distribution of seasonal lakes impacts the spread of Guinea worm. Guinea worm cases are known to be more common near infected sources of water (Royal 2013). As those drinking contaminated water are more likely to be local residents, this is unsurprising; however, it is necessary to define precisely who drinks this water and where they live, not because some areas of the lake are more infected with Guinea worm larvae than others, but because people living near infected lakes may have particularly at-risk behaviors.

The Carter Center, a major player in the Guinea worm eradication community, collects location data for Guinea worm-infected individuals in order to coordinate various monitoring and eradication programs. However, precise geographic information regarding the bodies of water used by the infected individuals is not always recorded. Although, in the past, bodies of water suspected of containing the parasite have been treated with larvicides, this method of combating the spread of Guinea worm is not preferred. Temaphos, the chemical most commonly used to combat Guinea worm, is an organophospate larvacide used to treat water infested with disease-carrying insects. Larvacides of this type kill the water flea (*Cyclops*) which serves as a host for Guinea worm larvae, effectively halting the parasites reproductive cycle. Larviciding has been controversial

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in that, in addition to killing the Guinea worm larvae, it kills other larval life and there are fears it may negatively affect those drinking the water. Additionally the lack of available safe drink water infrastructure causes the need for action such as larvaciding, which is no more than a temporary solution. Eradication through larvacides does not protect individuals who choose to travel beyond the watershed of a lake that has been treated with larvacides. Thus, efforts have focused on teaching individuals how to contain the spread of Guinea worm and how to avoid becoming hosts themselves (Rwakimari *et al.* 2006), rather than focusing on larvaciding the water supplies.

The vast majority of remaining Guinea worm cases occur in regions that endure some form of water stress during the annual cycles of rain (Lebel *et al.* 1992). Rainfall in these regions, primarily in the Sahel of sub-Saharan Africa, is seasonal; the annual pattern begins with several dry months with little or no precipitation, followed by a rainy season that lasts from three to five months. These Sahelian regions often have a limited water infrastructure, forcing inhabitants to be reliant on the local supplies of water (Giordano 2006). Drinking water is often drawn from unclean surface water sources, such as ponds, streams, lakes, and sometimes even from watering holes serving livestock. Water clarity is often poor, making a visual inspection for water fleas difficult. As an alternative to surface water, underground water is sometimes either drawn from wells or, less commonly, pumped to the surface using electric or hand-powered water pumps. While the subsurface water sources are free from Guinea worm larvae, there are not enough existing wells and pumps to support the inhabitants of the Sahel. Additionally, migrations and agricultural activities regularly draw the at-risk populations away from the cleaner water sources (Cairncross *et al.* 2002).

Detailed information on bodies of water that are capable of supporting the water flea and Guinea worm larvae is complicated by the seasonality of the precipitation in Sahelian regions. Throughout most of the Sahel evapotranspiration rates of the lakes are quite high due to high temperatures, low humidity, and sparse vegetation. Rainfall often occurs in great deluges rather than moderate, intermittent rains; flooding of the lowlands is an annual threat. Lakes and rivers, in some cases several kilometers long or wide, may flood seasonally and then dry up completely during the course of the year, making them difficult to map (Nicholson *et al.* 2000). While the fill levels of these bodies of water may vary according to the local precipitation rates, they are also affected by flash flooding. Many bodies of water are part of seasonal river systems that may flood hundreds of miles downstream when rainfall is sufficient in other areas of the watershed. Additionally, the desertification of much of the southern Sahel has caused changes in watershed dynamics (Leblanc *et al.* 2008). This changing environment is difficult to monitor, although recent efforts to collect data on water use and groundwater recovery have been undertaken by several countries through the actions of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) International Hydrological Program.

## STUDY AREA

The study area for this research comprises the majority of the Tillabéri *arrondissement* (borough) of northeastern Niger where there was a brief resurgence of Guinea worm cases in 2003 (Table 1). The area is centered on the city of Tillabéri, the capital city of the Tillabéri *arrondissement* and the focus of the study is on Tillabéri city and the surrounding region. This region is at an intersection of Saharan trade networks and is at the northernmost extent of Sahelian agriculture in eastern Niger (Figure 1). The population of approximately 200,000 in the region is divided into three tribal groups: the Zarma (Djerma), who traditionally work as farmers or merchants, and the Fulani and the Bella- or Tomacezk-speaking people, who are nomadic and semi-nomadic pastoralists. While Zarma is the dominant language of the region, each tribe speaks its own dialect as well.

Even for Niger, the Tillabéri study region is very dry. Precipitation primarily occurs in June, July, and August,

**Table 1** | Guinea worm cases by year

| Year | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|
| Cases in study region | 44 | 175 | 152 | 165 | 54 |
| Cases in Niger | 48 | 293 | 233 | 183 | 110 |
| Cases worldwide | 54,638 | 32,193 | 15,912 | 10,674 | 25,217 |

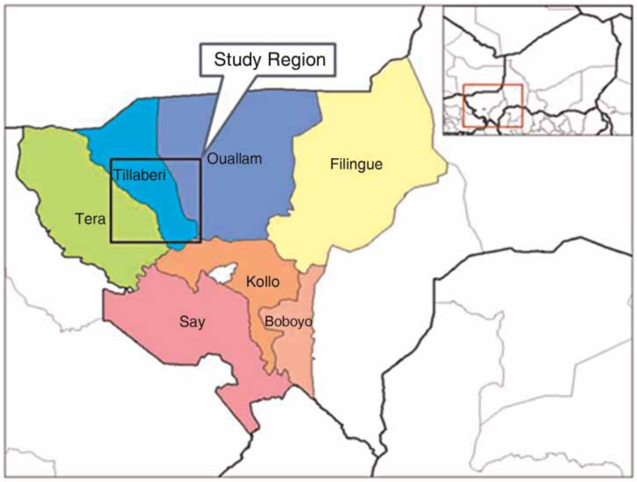

**Figure 1** | Extent of the study region.

averaging between 400 and 1,200 mm annually. Water is scarce during the dry months. Agricultural activities occur predominantly during the rainy season, when the landscape changes from an arid, rocky, and sandy wasteland to green fields of millet, sorghum, and beans. Seasonal lakes, which can grow to several kilometers long during the rainy season, often dry up entirely during the hottest months of the year when the temperatures can top 50 °C. The study area contains 32 seasonal lakes, each of which is represented by a single point; known as 'vanish points', these points were determined by the Nigerien Ministry of Hydrology to be the lowest and final points of water for each lake before it evaporates completely. There are no permanent lakes within the study region. The water bodies these points represent are the largest surface water bodies in the study region and were filled during every year of the study. These vanish points are important for this study as they represent the locus of congregation for people using the last of the lake water. The concentrations of Guinea worm are at their highest immediately preceding the complete evaporation of a body of water; thus, Guinea worm is most likely to be spread during a critical period of water stress (Adekolu 1983).

Details regarding the location, type, and depth of each well in the area were made available for this study by the Ministry of Hydrology, so as to enable a complete assessment of the available water resources. Trail and road datasets were donated by the Africa Data Dissemination Service, detailing 524 km of roads and 1,598 km of trails in the study site. Roads are differentiated from trails as roads are classified as vehicle-serving transportation routes. While similar to trails in that they are often unpaved, roads have been reinforced with compacted stones to prevent vehicles from sinking into the often-sandy terrain. Only one road in the region is paved: the route connecting Tillabéri to Niamey to the south and Mali to the north.

With the onset of the rainy season, pastoralists communities are obliged to journey to more remote pasture land to avoid interfering with crop cultivation. While many herding migrations will stay within or near the outskirts of a town, some will undertake much longer journeys. In the Tillabéri region of Niger, Fulani- and Tomaczek-speaking herders will move animals north into Mali, using a series of seasonal lakes as watering stops on the trip (Figure 2). Population centers and farmed fields are avoided during these migrations by traveling on a network of paths through unfarmed land. The number of livestock on this northward procession may vary from year to year, contingent on the rainfall and fill of each lake, as well as the rainfall in the pasture areas in southeastern Mali, near the Niger border. Desertification and insufficient precipitation in the Mali pasturelands impedes cultivation of the local grain staples of millet or sorghum (Mohamed 2013). However, there is enough rainfall suitable for grasses, enough ground water to keep the arriving herds of animals hydrated, and the lands are free from grazing limitations and land-use conflicts with farmers. After three to four months of grazing the animals in relative isolation in the north, the pastoralists return with their herds after harvest to feed the animals on the crop gleanings in the fields in their hometowns in Niger.

The locations of nomadic routes were documented during field research between January and June 2010. With help from local pastoralists the 281 km of nomadic trails were mapped. The coordinates of medical facilities were also identified through field research. Medical facilities in the region were of three different types: medical stations (six), medical centers (five), and hospitals (one). Medical stations were staffed by a single nurse and functioned as pharmacies and clinics. Diagnosis, provision of medicine and injections, assistance for births, and the pronouncement of death are the services provided by the nurse and staff at a medical station. Contacting the regional hospital and forwarding ill patients to more complete medical facilities via

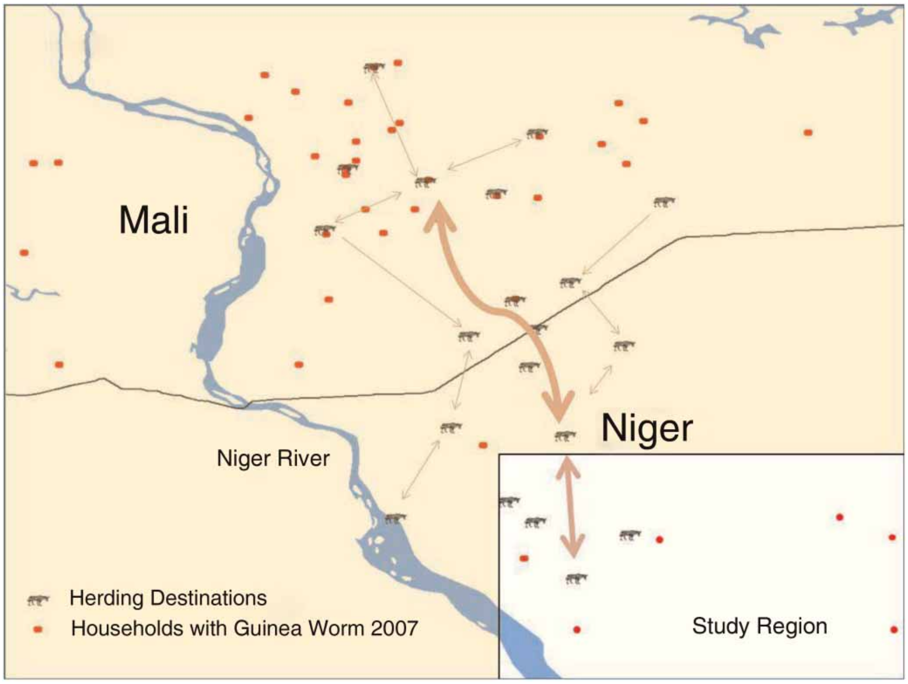

**Figure 2** | Herding paths used between the northern Tillabéri region of Niger and southeastern Mali.

ambulance is also a function of the medical station. Most medical stations have no electricity. Medical centers are similar to medical stations except they are larger, have more extensively trained nurses, have electricity, other staff to aid the nurses, a vehicle, and a radio tower to communicate with other medical facilities and hospitals. The region had only one hospital in the capital city of Tillabéri. The hospital was fully equipped, and was staffed by a variety of doctors, specialists, and others. Guinea worm eradication efforts were managed out of the Tillabéri hospital, but all medical facilities and staff in the region were part of the eradication effort.

## METHODS

Since very few demographic statistics are available for the Tillabéri region, analysis of the effects the built environment has on disease spread is the next best solution. Health facilities, transportation networks, and water sources all contribute to the living conditions of those at risk of Guinea-worm infection. The locations of wells, roads, trails, nomadic routes, and health facilities were examined to assess their effect on the incidence of Guinea worm in the study area. Each feature was selected because of its role in propelling people toward Guinea worm-infected regions or because of its role in educating or providing alternatives to the utilization of contaminated water.

The Carter Foundation had identified Guinea worm cases and the locations of where those infected were living for the study region for the period from January 2002 to December 2006. This dataset was made available to this study and it was placed in a geographic information system along with data pertaining to the locations of features of the built environment. Through interviews with health agents and previously infected individuals, it was determined which lake was presumed to infect each infected individual during the study period. Twenty-two of the 33 lakes in the region had no cases of Guinea worm associated with them while 11 lakes had associated cases of Guinea worm.

As each lake serves a certain population, the risk of exposure to Guinea worm larvae varies within the study region. In order to appropriately model the relationship between the incidence of Guinea worm in each lake and distances to features of the environment, it is important not only to understand how many cases of Guinea worm are associated with each lake, but also how many people the Guinea worm larvae in each lake could have potentially infected. Ideally, exposure to the Guinea worm larvae in each lake could be measured by the sum of the number of trips taken to each lake by the population the lake serves over a specified time period in combination with the numbers of infected *Cyclops* within each waterbody. However, this data is unavailable and gathering this data during field work was deemed unfeasible. Instead, the log of the area of each lake was included in the statistical models used in this analysis as an offset to serve as an indirect measure of exposure. This log-area method assumes that the population density in the service area is uniform. While this is certainly not the case, it is the preferred method of measuring exposure for this study region, as the population here is widely and relatively evenly dispersed across the terrain and engaged in agricultural work during the start of the dry season, when the risk of contracting Guinea worm is highest (Périès *et al.* 1998). The area associated with each lake was determined using Thiessen polygons centered at the location of the lakes' vanish points using the study site borders as a bounding box. The log of the area associated with each lake was used rather than the actual square kilometer area to normalize the great size differentials between the areas each lake serves (Figure 3).

One suitable method to analyze the relationship between the locations of Guinea worm-infected water supplies and the built environment relies on using a zero-altered negative binomial model, otherwise known as a hurdle model with a negative binomial second stage. Hurdle models are a type of discrete mixture models used for count data when there is an excess of zeros in the data. When a dependent variable contains more zeros than would be expected for a negative binomial distribution, these excess zeros are better managed through the use of a two-model approach; if these excess zeros are not included in the model, the parameter estimates and standard errors may be biased. The hurdle model used in this analysis examines the proximate relationship between lakes with associated cases of Guinea worm disease, as well as the

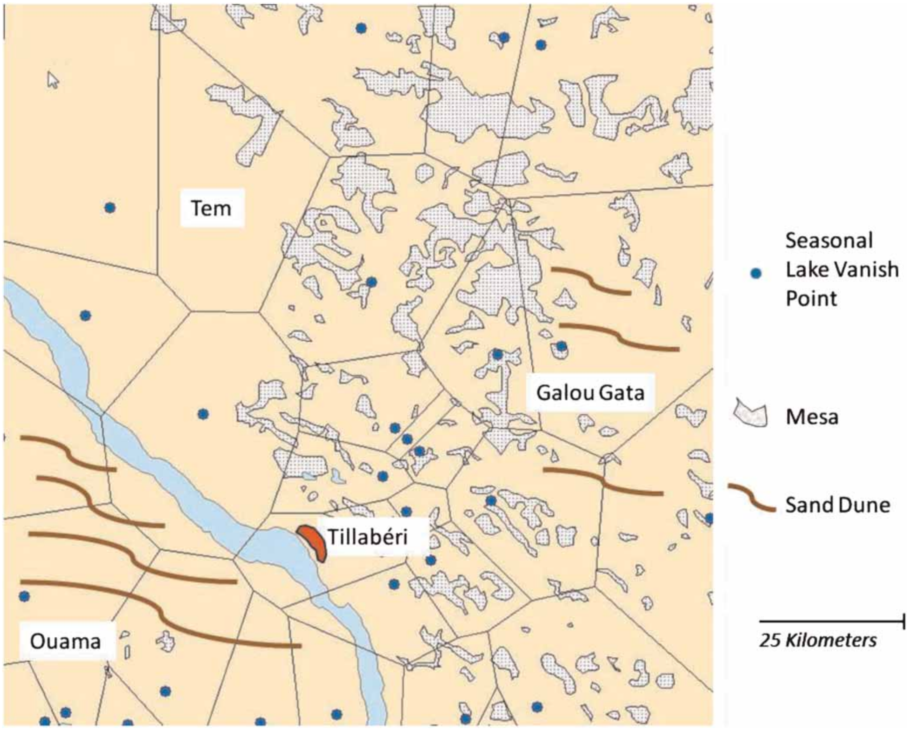

**Figure 3** | Areas associated with each lake within the study region.

lakes' proximate relationship to the built environment.

$$f\,\text{zero} - \text{altered negative binomial}\,(y;\beta,\gamma) = \begin{cases} f\,\text{binomial}(y=0;\gamma) & y=0 \\ (1-f\,\text{binomial}(y=0;\gamma))\times\dfrac{f\,\text{negative binomial}\,(y;\beta)}{1-\text{negtive binomial}\,(y=0;\beta)} & \\ & y>0 \end{cases}$$

where $y =$ counts of Guinea worm, $\beta =$ the distances from vanish points to built environment features, and $y =$ regression parameters (features of the built environment used in model) (Zuur *et al.* 2009).

The hurdle model was chosen to analyze the relationship between the associated cases of Guinea worm in each lake and the proximity to features of the environment over several possible models. Considering that the over-dispersion in the data is due *not* to the large differences in the numbers of associated cases of Guinea worm per lake, but rather to the large number of lakes without associated cases, the hurdle model is more suitable to this study's analysis than ordinary linear or negative binomial models (Greene 1995). The first stage of a hurdle model estimates the probability of achieving a zero value; once accomplished, the second stage examines the dependent variables without zero values, thus dividing the process of analysis into two specialized examinations.

Any hurdle model has two stages to its analysis as it is effectively a two-model approach. The hurdle model with a negative binomial second stage used in this analysis is one of two types of statistical model referred to as hurdle models. While the first stage of any hurdle model consists of a binomial generalized linear model, the second stage can be either a negative binomial model or a Poisson model. In terms of this study, a binomial generalized linear model is utilized to analyze the location differences between lakes with and without Guinea worm; and either a negative binomial or Poisson generalized linear model can be utilized to analyze the location differences between lakes with different counts of Guinea worm-associated cases (Figure 4). Analyzing each version of the hurdle model, including the log-area offset to account for exposure, the negative binomial version of the hurdle model is the preferred model for this analysis according to the results of an

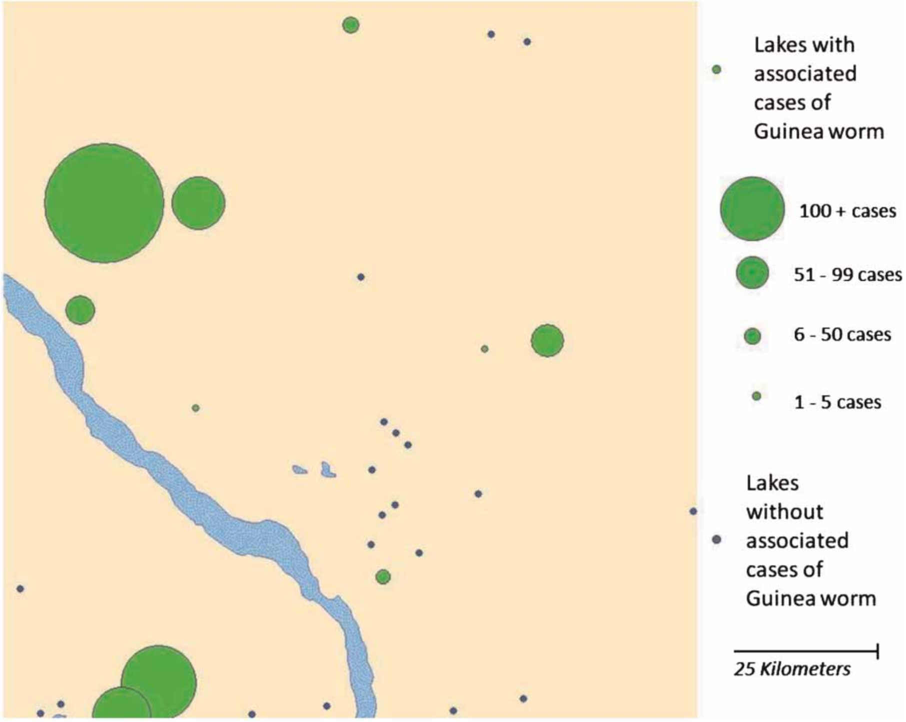

**Figure 4** | Cases of Guinea worm associated with each lake within the study region.

Akaike information criterion (AIC) test, which is a measure of the relative goodness of fit for statistical models. A model's AIC score is calculated using the following equation:

$$\mathrm{AIC} = 2k - 2\mathrm{Ln}(L)$$

where $k$ is the number of parameters in the model and $L$ is the maximized value of the likelihood function for the estimated model (Akaike 1987).

The preferred model for this analysis is one with a low AIC, as the lower the AIC, the less information will be lost when describing the relationship between number of associated cases per lake and the surrounding environment. The AIC measures the balance between model fit and parsimony. When two models with the same likelihood value (fit) but with different numbers of parameter estimates are examined, a model selection decision using AIC will select the model with fewer parameters.

A Poisson model offers an alternative to the hurdle model for examining this dataset. The formula for a Poisson model with the aforementioned log-area offset is as follows:

$$\log(\mu_i) = \log(A_i) + X_i\beta$$

where the offset, $\log(A_i)$ is the log of service area of the lake, $\mu$ is the numbers of associated cases, and $\beta$ is the distance between lakes and the environmental feature.

As there is a Poisson distribution of the case count data, a Poisson model is included in the AIC test in order to validate the use of a two-stage model.

## RESULTS

In comparing the two variants of the hurdle models (negative binomial and Poisson), the negative binomial variant has an AIC score of 145 and the Poisson hurdle variant has an AIC score of 207 (Table 2). A Poisson model with the log-area offset, the next most suitable regression model for this analysis, underperforms both hurdle models with an AIC of 581. Examining a scatter plot of the fitted values estimated for each model against the model's residuals shows that the hurdle model with a negative binomial second stage performs similarly to the hurdle model with a Poisson second stage as well as the Poisson model (Figure 5).

**Table 2** | AIC tests comparing a hurdle model with negative binomial second stage and hurdle model with a Poisson second stage

| Model type | Degrees of freedom | AIC score |
|---|---|---|
| *Zero altered Poisson* | | |
| Hurdle model | 12 | 207.320 |
| *Zero altered negative* | | |
| Binomial hurdle model | 13 | 145.072 |
| Log-rate model | 6 | 581.050 |

Poisson models can struggle to handle ancillary zero counts, just as negative binomial models do if the ancillary zero values are too numerous (Greene 1995). In the case of this analysis, the ancillary zero counts represent the lakes without associated cases of Guinea worm. As the proportion of lakes without associated cases of Guinea worm is two-thirds the total number of lakes within the study region, it is probable that a Poisson model would be more suitable for an analysis examining other regions where there were fewer lakes without associated cases of Guinea worm.

For each model, lakes with larger residual values have higher predicted case counts, with the Poisson model fitting slightly higher case counts to lakes with higher residual values than either of the two hurdle models. However, as the AIC shows that the hurdle model with a negative binomial second stage describes the relationship between the dependent and independent variables with the least loss of information, the test confirms it is the preferred model for this analysis.

In the first stage of either hurdle model (the binomial generalized linear model), the lakes are separated into those with associated cases of Guinea worm and those without. The number of cases of Guinea worm associated with each infected lake is not examined; only the presence or absence of cases is noted. Lakes *without* Guinea worm are examined to identify what it is about their location and their proximity to features of the built environment that distinguishes them from lakes *with* associated cases of Guinea worm (Table 3). The distinction between an infected lake and an uninfected lake is examined in terms of distance (in kilometers) from the vanishing point of a lake to a

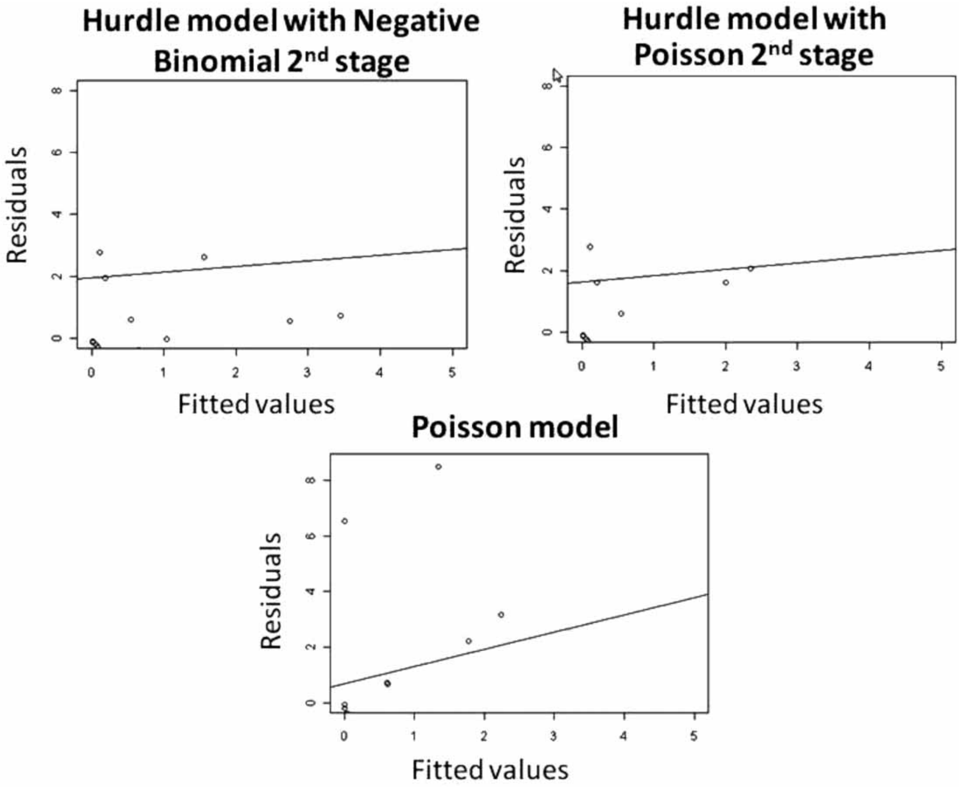

**Figure 5** | Fitted values and residuals for each of the tested models.

**Table 3** | Distance from seasonal lakes to environmental features (in kilometers)

| Lake ID | No. of Guinea worm cases | Wells | Nomadic | Health | Trails | Roads |
|---|---|---|---|---|---|---|
| 11 | 265 | 4.81 | 2.94 | 9.86 | 4.24 | 14.89 |
| 13 | 105 | 1.63 | 6.31 | 4.74 | 13.13 | 9.37 |
| 14 | 10 | 4.54 | 5.65 | 3.41 | 1.17 | 1.64 |
| 15 | 1 | 10.41 | 3.58 | 12.21 | 2.41 | 14.7 |
| 18 | 0 | 11.65 | 15.12 | 1.06 | 0.24 | 10.41 |
| 19 | 0 | 2.71 | 17.31 | 9.92 | 4.57 | 5.064 |
| 20 | 0 | 15.02 | 5.62 | 12.10 | 0.95 | 0.99 |

built-environment feature (Figure 6). In comparing the positioning of the lakes in relation to the proximate built environment, each lake's spatial distribution within the built environment can be examined in terms of its relative isolation or nearness to features that are presumed influential to the spread of Guinea worm. The second stage of a

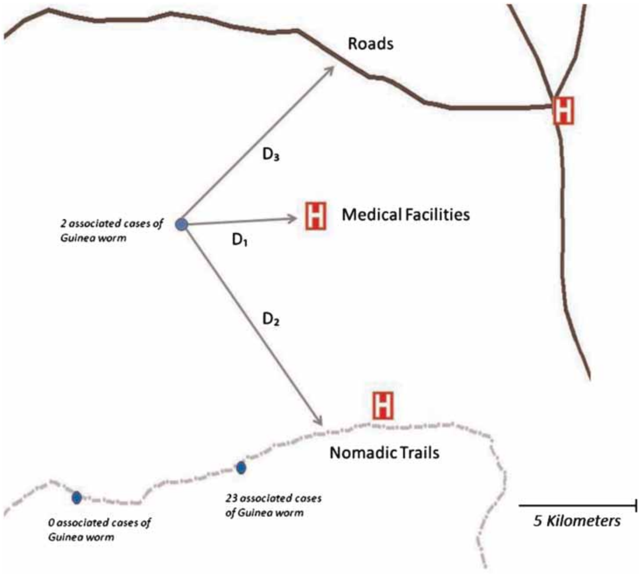

**Figure 6** | Example of measuring the distances from lake vanish points to features of the built environment.

hurdle model reveals the differences within lakes with cases of Guinea worm; lakes without Guinea worm are excluded. Each infected lake's relationship to the built environment is once again examined, this time comparing the lakes to each other in terms of the counts of associated Guinea worm cases, rather than simply noting the presence or absence of Guinea worm.

The results of a hurdle model with a negative binomial second stage suggest that there is a significant correlation between health facilities and lakes with Guinea worm and between lakes with Guinea worm and the location of trails (Table 4). In the analysis of lakes with and without Guinea worm, there is a negative correlation between health facilities near a lake and the incidence of Guinea worm; suggesting the closer a health facility is to a lake, the higher the likelihood of Guinea worm being present in the lake. In the second stage of the hurdle model (the negative binomial count model), the health facility is again negatively correlated, suggesting that the more cases of Guinea worm associated with a lake, the nearer the health facility is to the lake.

**Table 4** | Hurdle model results

**Stage 1: Hurdle model (binomial with log link)**

| | Estimate | Std. Error | Z value | Pr(>\|z\|) |
|---|---|---|---|---|
| (Intercept) | 1.9796 | 0.6631 | 2.985 | 0.0028 |
| Health | −0.3210 | 0.0768 | −4.180 | <0.0001 |
| Wells | −0.0135 | 0.0585 | −0.230 | 0.8177 |
| Trails | 0.4602 | 0.2075 | 2.210 | 0.0266 |
| Roads | −0.0364 | 0.0340 | −0.911 | 0.3623 |
| Nomadic | −0.0378 | 0.0258 | −1.469 | 0.14185 |

**Stage 2: Count model (truncated negative binomial with log link)**

| | Estimate | Std. Error | z value | Pr(>\|z\|) |
|---|---|---|---|---|
| (Intercept) | 3.9263 | 1.9372 | 2.0270 | 0.043 |
| Health | −0.2652 | 0.1008 | −2.630 | 0.008 |
| Wells | 0.0243 | 0.0722 | 0.337 | 0.736 |
| Trails | −0.4354 | 0.2584 | −1.685 | 0.092 |
| Roads | 0.0922 | 0.0754 | 1.224 | 0.221 |
| Nomadic | 0.0383 | 0.0462 | 0.829 | 0.407 |
| Log(theta) | 0.27 | 0.64 | 0.43 | 0.670 |

Theta count = 1.5258; log-likelihood: −59.54 on 13 degrees of freedom.
Person residuals: Min: −1.4801; 1Q: −0.5777; median: −0.3972; 3Q: 0.4983; max: 2.7665.

## DISCUSSION

Examining the locations of all the health facilities in the geographic information system reveals that the four health facilities closest to lakes were at the very center of two of the three most infected regions. Each of these four facilities is a medical station. The health facilities in these locations were also close to the vanishing points of the lakes, located on the banks of the seasonal lakes during the parts of the year they were completely filled. Each of these medical stations was close to a moderately sized (<1,250 persons) population center. It is worth noting that health facilities were not always located within the borders of large population centers; in fact some were several kilometers from any population center. Many of the other health facilities, particularly in regions without Guinea worm, were not positioned near lakes and were located on higher terrain and comparatively far from lakes. This neither proves the usefulness of the model nor refutes its findings, although it does suggest that a comparative analysis at a larger scale–with more health facilities in a larger area–would be insightful.

The model results also reveal a relationship that exists between the location of trails and whether or not a lake will have associated cases of Guinea worm. Given the results of the model it is suggested that the farther a trail is from a lake, the more likely the lake is to have at least one associated case of Guinea worm. Conversely, infected lakes near trails also tended to have more associated cases than infected lakes that were distant. The effects of other transportation networks on the spread of Guinea worm and on the lakes are unclear. There is little evidence of correlation between wells and Guinea worm-infected lakes, although given the large number of the wells in the study region it could be that their statistical effects are unclear since they are proximate to most features of the natural and built environment.

Human travel behavior is a critical factor for determining the boundary of the spread of Guinea worm (Royal 2013). The destination choices of humans traveling through the Tillabéri region determine the locations to which Guinea worm spreads. Local transportation choices appear to be just as important in determining the vulnerability to Guinea worm as more distant locations. Whereas the disease must first arrive in a region of re-emergence from a distant location, its spread locally appears to result from travelers moving along local trails. Trails passing by lakes with Guinea worm logically increase the lake's exposure and, in turn, provide a community of hosts for the parasite. Those traveling by trail often travel by foot or pack animal and a readily available water source may have even influenced the trails location, as travelers through the desert often want for drinking water. Lakes isolated from all transportation networks are those which travelers are less likely to frequent. Given the farming practices in the region, it is likely that these lakes are in remote areas and only used by hunters or by farmers at their *zigi.* (The *zigi* is the 'far field', that is a field of crops in another locale to the farmer's usual habitation.) Many of those individuals who embark on *exode* (seasonal migration) will return to their homes in time to farm. Future work may benefit from further investigation into whether or not lakes in remote areas far from transportation networks are becoming infected by individuals returning from *exode* or other long-distance travels.

Relationships between health facilities and regions with high incidence of Guinea worm are of great importance to eradication efforts. Regional health facilities monitor and treat infected people, and their cooperation with health officials and eradication workers has been invaluable. Finding correlation between the locations of health centers and in the location of cases is clearly troubling as it supports three possible explanations as to why such a relationship exists. The least contentious of these possible relationships is that health facilities were placed in regions where there were high incidences of Guinea worm. Older maps (circa 1960) of the Tillabéri region show health facilities in only four locations in the study region, whereas in the past 50 years there has been a threefold increase in their number. Regions with Guinea worm cases are often remote and deprived of basic infrastructure–a condition that would increase the relative incidence of many diseases, not just Guinea worm. Thus, health facilities may have been built in these regions to combat poor health conditions, which would result in endogeneity in the models. If the starting dates of operation for each of these medical facilities exist, further analysis may support this possibility. Unfortunately, no data on when these medical facilities began to receive patients could be uncovered, and further field work would be required to fully eliminate the possibility of endogeneity in the model used for this analysis.

Another possible relationship between the locations of health facilities in relation to Guinea worm-infected lakes is that there is a correlation between the residential location of infected people and their proximity to health facilities. This analysis assumes that all cases in the Tillabéri region are accounted for; there is little evidence to suggest that the Guinea worm monitoring efforts have been anything less than extraordinarily well organized and determined, although the possibility of incomplete reporting of Guinea worm cases certainly exists. Migrant populations, who are often absent in Niger during some seasons of the year, are difficult to monitor and account for in the annual Guinea worm census. When migrant Guinea worm-infected individuals return to Niger, their proximity to health facilities is almost certainly a factor in their willingness to report themselves to the eradication community. Further information as to the numbers of persons traveling in and out of the study region as well as the numbers of people who use each health facility would allow a further understanding of this possibility.

Finally, persons traveling to or from health facilities may infect or become infected by the local water sources on the way. Just as health centers are the nexus for medical treatment they may also serve as a catalyst for its spread. Other factors that localize traffic into certain regions such as schools, jobs, religious centers, festivals, etc. would be useful to fully understand why people travel where in the region and how these health facilities affect travel. Each health facility has its own administrative boundary for the communities it serves, and Niger law is such that it encourages citizens to visit only their regional medical facility. Any prevalent communicable disease in a town with a health facility puts a traveler visiting the health facility for another illness at risk of becoming infected by a local epidemic. This forced the regionalized health care to become institutionalized through the decentralization laws that were put in place during Mamadou Tandja's (1999–2010) presidential administration. They were instituted to keep communicable diseases more locally contained. Quarantining may also raise infection rates; having a single destination for health care creates a highly contagious environment. Most carriers do not know they have Guinea worm until the parasite is at the oviposition stage and ready to expunge its eggs. Recovering or treated individuals leaving a health facility also risk contact with Guinea worm on the way home to other parts of the region. They are more likely to be unfamiliar with which water sources in the area are free of Guinea worm, therefore having a greater risk of contracting the parasite.

## CONCLUSIONS

While the methods of this model suffer from small sample size, in that there are so few water bodies in the region suitable for Guinea worm, the evidence suggests that the relationship between health facilities and Guinea worm infection is not ideal for the model of eradication currently employed. The assumption that all cases of Guinea worm are being recorded and found is either incorrect, or health facilities (or some undiscovered spatial correlate to them) may be affecting the spread of Guinea worm and/or are ineffective in reducing the numbers of proximate cases. Both issues are clearly problematic for eradication efforts; solutions that change either the way Guinea worm cases are identified or how health facilities prevent local outbreaks of the parasite are needed. It is important to remember that Guinea worm is not merely a Sahalien disease, or one confined to a limited geographic region–in the past Guinea worm was found all through North Africa, the Middle East, and Southern Asia. Guinea worm disease still has the potential to be an emerging pathogen, despite its currently limited numbers. Further research on the exact ways in which health facilities impact the spread of Guinea worm would be the next logical step. It may be that as health facilities are normally situated in larger towns and Guinea worm cases are clustering around health facilities, urban populations without clean water sources may be more at risk for Guinea worm in the late stages of eradication efforts.

The destination and route choice involved in travel behaviors, once understood, can help manage and mitigate their effects in encouraging the spread of Guinea worm. This model offers some insight into which behaviors of locally traveling individuals put themselves and others at risk of Guinea worm. Understanding the health needs of these high-risk individuals and their behavior may provide the key to finally eradicating the parasite.

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