

Hydrologic modeling to screen potential environmental management methods for malaria vector control in Niger

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[1] This paper describes the first use of Hydrology-Entomology and Malaria Transmission Simulator (HYDREMATS), a physically based distributed hydrology model, to investigate environmental management methods for malaria vector control in the Sahelian village of Banizoumbou, Niger. The investigation showed that leveling of topographic depressions where temporary breeding habitats form during the rainy season, by altering pool basin microtopography, could reduce the pool persistence time to less than the time needed for establishment of mosquito breeding, approximately 7 days. Undertaking soil surface plowing can also reduce pool persistence time by increasing the infiltration rate through an existing pool basin. Reduction of the pool persistence time to less than the rainfall interstorm period increases the frequency of pool drying events, removing habitat for subadult mosquitoes. Both management approaches could potentially be considered within a given context. This investigation demonstrates that management methods that modify the hydrologic environment have significant potential to contribute to malaria vector control in water-limited, Sahelian Africa.

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1. Introduction

[2] Malaria continues to place a large social and economic burden on African communities. Modern programs to control malaria transmission typically target the adult primary vectors, using techniques such as bed nets and indoor residual spraying that have a high impact on vectorial capacity. However, these methods are vulnerable to development of vector resistance to insecticides [Hargreaves *et al.*, 2003; Stump *et al.*, 2004; Reimer *et al.*, 2005; Casimiro *et al.*, 2006], vector behavioral adaptation, such as changing preferences for feeding and resting outdoors [Killeen *et al.*, 2002], and logistics and funding problems in reaching the poor who are most at risk [Barat *et al.*, 2004].

[3] Environmental management of malaria involves either modification of the environment, to permanently change conditions to reduce malaria vector habitats, or manipulation of the environment, to temporarily create unfavorable conditions for malaria vector propagation [World Health Organization (WHO), 1982]. Historically, environmental management methods that targeted the larval stages of malaria vectors were effective in substantially reducing malaria transmission [Soper and Wilson, 1943; Shousha, 1948; Keiser *et al.*, 2005]. These methods fell out of favor with the widespread introduction of synthetic insecticides and bed nets, which reduce biting rates, decrease survivability of vectors, and are not dependent

on such site-specific knowledge as is required for larval control methods [Carter *et al.*, 2000; WHO, 2006]. However, the United States Agency for International Development (USAID) has stated that environmental management is the method of choice for mosquito control when the mosquito species targeted are concentrated in a small number of readily identifiable discrete habitats [United States Agency for International Development, 2007]. Also, the World Health Organization (WHO) has suggested that environmental management may be effective in reducing environmental risk factors for transmission of disease and for controlling transmission in areas with issues of resistance to synthetic insecticides [WHO, 1995].

[4] Integrated vector management programs, employing a variety of tools for targeting both adult and subadult vector stages, may provide the greatest chance for success in reducing malaria transmission rates [Walker and Lynch, 2007]. Methods that target the aquatic breeding habitats of mosquitoes have the potential to be effective, low cost, and with low environmental impact [WHO, 1995; Utzinger *et al.*, 2001; Killeen *et al.*, 2002; Konradsen *et al.*, 2004]. These methods not only reduce the emergence of adult mosquitoes, by increasing subadult mortality, but also increase adult mosquito mortality because of the increased length of time that adults spend foraging for a reduced number of suitable oviposition sites [Killeen *et al.*, 2004; Gu *et al.*, 2006]. If modern-day environmental management is to be a useful addition to the toolbox of malaria abatement methods, it will need to be low cost and sustainable in order to be attractive to national and international malaria control programs.

[5] Modeling tools can be used to simulate the effect of various kinds of environmental management, including larval control, on vector abundance and malaria transmis-

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sion, to determine a priori the most suitable methods for a given location. *Killeen et al.* [2004] used a mosquito resource availability model to simulate the effect of water management, larvicide application, physical domestic protection, and zooprophylaxis on various aspects of malaria transmission in Tanzania, including emergence rate, host availability, habitat availability, and entomologic inoculation rate (EIR). All the simulated interventions significantly suppressed transmission but interventions to reduce available habitat were the most efficacious method [*Killeen et al.*, 2004]. *Gu and Novak* [2005] used a mosquito population model to investigate how extensive a larval control program would need to be in order to have a significant impact on malaria prevalence and incidence in low to intermediate transmission areas. Their results showed that only 40% coverage of habitats was required to achieve a 70% reduction in the total productivity, if larval controls were appropriately targeted to the most productive sites. Under conditions of an intermediate level of malaria transmission, this reduction in productivity translated to a 70% reduction in EIR and a 66% reduction in malaria incidence [*Gu and Novak*, 2005]. These two studies illustrate the potential contribution of environmental management to malaria control but, because they involved modeling only of the mosquito populations, do not convey much information about the management methods or the impact on the physical environment.

[6] This paper describes a hydrologic modeling investigation into the potential for environmental management to contribute to malaria vector control in Niger, with a case study on Banizoumbou village in western Niger. The objective was to explicitly simulate environmental management interventions via changes to local topography and soil characteristics and to determine if the simulated methods would be efficacious in this context. This study represents a novel application of hydrologic modeling. Our model, Hydrology-Entomology and Malaria Transmission Simulator (HYDREMATS) [*Bomblies et al.*, 2008], provides a mechanistic means of representing known environmental determinants of malaria transmission, the first time to our knowledge that such a modeling attempt has been undertaken. With accurate representation of the relationships between the physical environment and mosquito populations and a fine spatial resolution, HYDREMATS can simulate the complexities of malaria dependence on environmental variables and therefore provide good predictive ability to test the response of mosquito populations to climatic variability or human interventions [*Bomblies et al.*, 2008].

[7] In particular, HYDREMATS was developed to evaluate the response of mosquito populations to hydrologic controls in the Sahel region of Africa using a distributed modeling approach. The life cycle of mosquitoes of the *Anopheles* genus is fundamentally dependent on local hydrology. The egg, larvae, and pupae stages of development are aquatic, and adult *Anopheles gambiae* mosquitoes in West Africa (the most important local malaria vector) breed almost exclusively in ephemeral, rain-fed pools. Also, rainfall events can affect the behavior of adult mosquitoes because the increased near-surface humidity associated with rainfall enhances mosquito flight activity and host-seeking behavior [*Shaman and Day*, 2007]. Therefore anopheline

mosquito abundance and malaria transmission are extremely sensitive to hydrologic variability, particularly fluctuations that affect the availability of suitable aquatic breeding habitats [*Shaman and Day*, 2005]. We have observed that, in and around Banizoumbou, ephemeral pools dry out completely after rain events, leaving no residual soil moisture and creating a hardened, cracked clay surface. We have also observed that anopheline larvae do not survive on such a surface, and areas that are rewetted after such desiccation have not been observed to contain late-stage larvae or pupae. Hence hydrologic controls on the persistence time of breeding pools are especially important in the region around Banizoumbou because the drying out of a breeding pool leads to death of an entire cohort of developing larvae and pupae, requiring the breeding population to begin again. Our model HYDREMATS can explicitly represent the small bodies of pooled water that form during the annual monsoon season and become mosquito-breeding habitat.

[8] This investigation involved numerical simulations of two interventions that target the larval stages of *Anopheles gambiae s.l.*, the primary malaria vector in western Niger, by minimizing the availability of breeding habitat during the rainy season. The two interventions simulated were leveling of topographic depressions where breeding pools typically form and plowing of the land surface to enhance processes for dissipation of breeding pools. These interventions were chosen for investigation because of their suitability to the local environmental conditions and vector dynamics, because they are low cost and require very few materials or resources, they do not rely on external sources of aid, and because they could be carried out by the residents of Banizoumbou in the long term in a sustainable manner.

2. Study Area

[9] Banizoumbou village is located in Sahelian southwestern Niger (13° 31' N, 2° 39' E), approximately 60 km northeast of the capital Niamey (see Figure 1), and is home to approximately 1000 people. Banizoumbou is representative of the many small villages in this region, being located in a semiarid landscape with gently sloping topography and vegetation cover comprising tiger bush, millet fields, and bare soil. The groundwater table lies approximately 25–30 m below the ground surface in the village and provides the only source of water for the residents.

[10] The long-term average annual rainfall in nearby Niamey over the period 1905–1989 was 562 mm [*Le Barbé and Lebel*, 1997], although drought during the period 1968–1990 reduced the recent average annual rainfall to 495 mm [*Le Barbé and Lebel*, 1997]. All of the precipitation occurs during the rainy season that extends from May to October and peaks in August during the height of the West African monsoon. In the region around Banizoumbou, rainfall drains from small catchments into topographic low points to form ephemeral pools, which have a width scale of several meters to tens of meters [*Desconnets et al.*, 1997].

[11] Within a closed pool basin, pool volume changes in response to inflows from concentrated runoff and losses from evaporation and infiltration. Even though the pools contain a low-permeability clayey base layer, observations of ephemeral pools in the region have shown that infiltration is responsible for approximately 90% of the pool losses [*Desconnets et al.*, 1997]. In Banizoumbou, we have

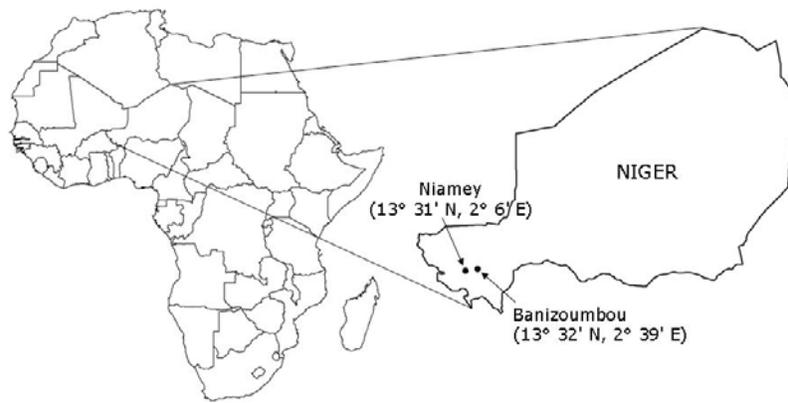


Figure 1. Location of Banizoumbou village within western Niger, approximately 60 km east-northeast of Niamey.

observed that these ephemeral pools do not develop complex ecosystems, in the sense of providing habitat for a variety of plants and animals at different trophic levels, and are not utilized by the residents. However, they do provide ideal breeding habitat for *Anopheles gambiae s.l.* mosquitoes, and hence the onset of the rains typically brings a substantial increase in mosquito populations and malaria transmission. Figure 2 illustrates the close relationship between seasonal rainfall and increases in malaria incidence in Niger.

[12] As discussed by *Bomblies et al.* [2008], smaller-scale pools around Banizoumbou, such as tire tracks and hoof prints, have occasionally been observed to contain mosquito larvae. However, these smaller-scale pools do not persist long enough to productively contribute to the adult mosquito population and therefore are only considered to be productive when they exist in saturated areas near a larger pool [Bomblies et al., 2008]. This investigation therefore only considered the larger pools that contribute to the adult mosquito population. Pools of this kind in Sahelian Niger could be highly suitable for environmental

management techniques because of their discrete and ephemeral nature.

3. Model Description and Calibration

[13] This investigation uses the hydrology component of the Hydrology-Entomology and Malaria Transmission Simulator (HYDREMATS) [Bomblies et al., 2008], which was developed for the mechanistic simulation of local-scale response of malaria transmission to hydrological and climatological determinants in semiarid, desert fringe environments. Borrowing heavily from LSX [Pollard and Thompson, 1995], the model combines calculation of vertical fluxes of water and energy within a column with determination of distributed overland flow, which allows runoff between grid cells to form small-scale pools [Bomblies et al., 2008]. The model explicitly represents with high temporal and spatial resolution the distributed pooled water that constitutes *Anopheles* mosquito-breeding habitat as well as the soil moisture that governs the formation of this habitat.

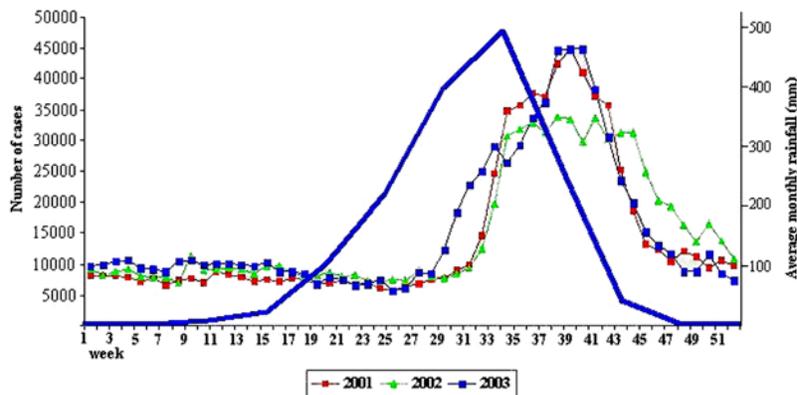


Figure 2. Relationship between malaria incidence and seasonal rainfall in Niger. The curves with markers show weekly malaria incidence in Niamey, Niger, from 2001 to 2003 (left-hand axis). The blue line shows monthly precipitation data averaged for the period 2001–2003 as derived from the Global Precipitation Climatology Project data set (right-hand axis). (Source: *Bomblies et al.* [2008].)

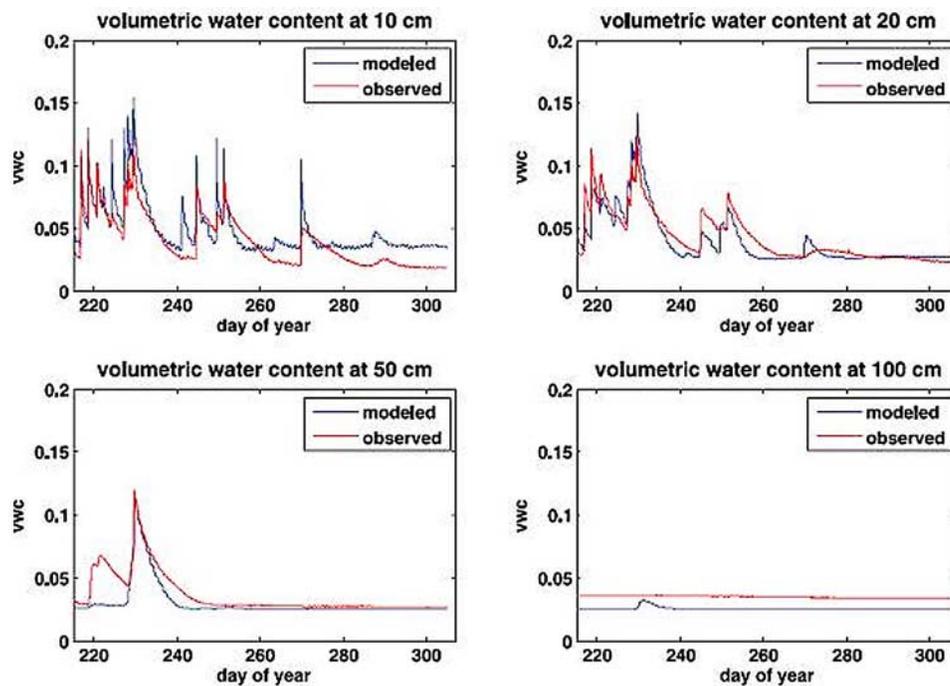


Figure 3. Model soil moisture output (volumetric water content) compared to measured soil moisture at a millet field 500 m north of Banizoumbou for the period 1 August to 10 November 2005. (Source: *Bomblies et al.* [2008].)

[14] For this study, the model was required to accurately simulate the pool water volume resulting from overland flow entering topographic depressions, creating mosquito-breeding habitat, and the persistence of these pools after formation. Therefore the model needed to accurately simulate the partitioning of rainfall into runoff and infiltration at the soil surface in order to represent both the total water flow entering a topographic depression and the soil water dynamics in the unsaturated zone. In order to meet these modeling requirements, the unsaturated zone hydrology model needed to be appropriately parameterized to reproduce the temporal behavior of soil moisture in the soil column as observed by in situ soil moisture sensors.

[15] The unsaturated zone hydrology model was calibrated as described by *Bomblies et al.* [2008]. Calibration was performed against field data collected during the 2005 rainy season, and the model was subsequently verified using field data from the 2006 rainy season. The model was calibrated primarily for the vadose zone, but surface soil crusting was also represented [*Bomblies et al.*, 2008]. The four parameters that were calibrated to match model output to field observations come from the Richard's equation and Campbell's formulation for soil water retention: the air entry potential (ψ_e), saturated hydraulic conductivity (K_s), Campbell's curve fitting exponent (b), and porosity (θ_s) [*Bomblies et al.*, 2008]. These four parameters for each discrete soil layer completely parameterize unsaturated zone water redistribution according to Campbell's model. Initial parameter assignments were made on the basis of typical values for the sandy soils of Banizoumbou and published values and were refined using a Gauss-Newton method. The objective function for this optimization is formulated as a least squares minimization (see *Bomblies et al.* [2008] for further details of the calibration process). Figure 3 shows unsaturated zone

hydrology model fit with TDR soil moisture profile data recorded at a measurement site in Banizoumbou and demonstrates good model fit to observations.

[16] Evaporation is calculated in the model as a turbulent flux that depends on the vertical wind shear, surface roughness, and humidity gradient across the water-air interface. The calculation does not include the effect of advection of air, which may lead to enhanced evaporation. However, during the rainy season, ambient humidity levels remain high (above about 60% relative humidity) and winds are typically light. Test simulations showed that exclusion of the "advection effect" leads to at most 10% error in total evaporation from water bodies over the course of a 4-month rainy season. Given that the flux of water out of pools in the region near Banizoumbou via infiltration has been shown to be an order of magnitude greater than evaporative fluxes [*Desconnets et al.*, 1997], the error in evaporative flux is considered insignificant and can reasonably be ignored.

4. Model Inputs and Grid

[17] The model domain spans an area of 2.5 km \times 2.5 km, centered on Banizoumbou village, with a total of 100 \times 100 grid cells. The domain contains telescopic mesh refinement, with the central area of the domain that covers the village containing the smallest grid cell sizes, and horizontal resolution decreasing with distance away from the center toward the edges of the domain. The central area is 500 m \times 500 m and covers the village with grid cells of size 10 m \times 10 m. Outside the center, in each direction, are 10 grid cells of length 20 m, followed by 10 grid cells of length 40 m and then 5 grid cells of length 80 m. The highest points within the domain are at 235 m above mean sea level, in the southwest corner, and the lowest points are at 204 m above mean sea level, to the north of Banizoumbou. The village

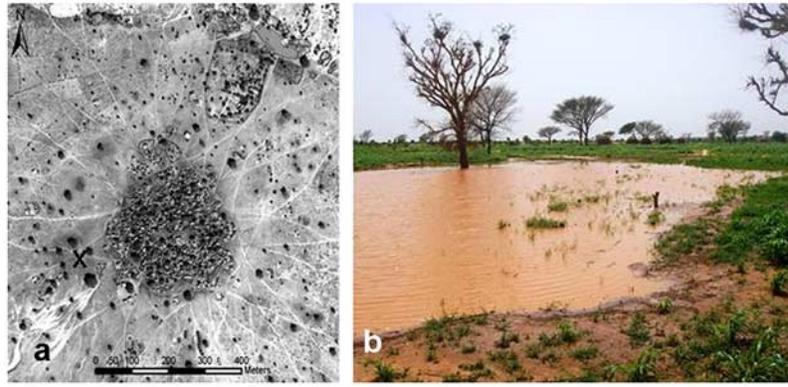


Figure 4. (a) Location of pool altered in modeling investigation (marked by black cross). The digital photograph is a Quickbird image taken in January 2003 during the dry season, ©2003 DigitalGlobe, Incorporated, All rights reserved. Quickbird file name: 03JAN28101757-P2AS-000000191594_01_P001. Date: 28 January 2003. Processing level for this image was standard ortho ready. (b) Pool used in the model simulations. Photograph taken 20 August 2007 with pool at approximately its maximum extent.

itself is located at approximately 210 m above mean sea level. Because of the small inner grid cell size of 10 m, the overland flow module operates at a time step of 1 s to meet conditions for stability, while the unsaturated zone model operates at a coarser time step of 1 h. Energy and water redistribution calculations are also performed at 1 h time steps.

[18] Vegetation cover and topography over the model domain have been specified using remotely sensed data as described by *Bomblies et al.* [2008]. Vegetation cover input is derived from a Landsat-7 multispectral image, using a supervised classification technique [Boyer, 2003]. The land cover around Banizoumbou has been designated as either savannah grassland to simulate either natural savannah vegetation or agricultural cropland, xeric scrubland to represent the tiger bush shrubs that are present on the lateritic plateaux in the region, or fallow field/bare soil. The model parameterizes root zone hydrology, transpiration, and surface roughness according to the land cover classification assigned to each grid cell [Bomblies et al., 2008]. A digital elevation model (DEM) was generated by radar interferometry using a stereopair from the Envisat satellite, with a ground resolution of 50 m [Bomblies et al., 2008]. Within and surrounding Banizoumbou village, the DEM has been refined to a 10 m resolution through a ground topographic survey with a total station (sourced from *Bomblies et al.* [2008]).

[19] Meteorological data were provided as inputs to the model for each of the simulation periods in 2005, 2006, and 2007. These data were collected at a meteorological station located just outside of Banizoumbou village, in a sparse millet field. Precipitation, relative humidity, wind speed, wind direction, air temperature, and incoming shortwave radiation were sampled and recorded every 15 min at the station. Meteorological variables are considered invariant over the model domain. The meteorological data were provided by Institut de Recherche pour le Développement (IRD) in Niamey, Niger.

5. Simulation Descriptions

[20] Modification of one pool within Banizoumbou was undertaken as a case study. The pool is located on the

outskirts of Banizoumbou to the southwest of the village, as shown in Figure 4a. This pool does not exist during the dry season, but during the rainy season it has been observed by the authors at a maximum size of approximately 60 m × 40 m and with a maximum depth of approximately 40 cm, as shown in Figure 4b. It is formed from surface runoff produced on the surrounding land and has a catchment area of approximately 48 ha. The pool is not used by the residents of Banizoumbou or their cattle. We have observed the pool to contain many subadult (larvae and pupae) *Anopheles gambiae s.l.* mosquitoes, and it is thought to contribute significantly to the mosquito populations that become abundant in Banizoumbou during the rainy season. The pool is typical of ephemeral breeding pools in the area and thus considered a suitable case study for investigation of environmental management interventions.

[21] This investigation simulated habitat modifications in the form of leveling the topographic depression where the pool typically forms and plowing the surface soils of the pool basin. For both interventions, the simulations were repeated using 2005, 2006, and 2007 meteorological observations as input data to determine how these techniques performed under different climatic conditions.

[22] The objective of both interventions was to reduce the length of time the pool persists (“pool persistence time”) each time it formed throughout the rainy season. The aquatic stage of the *Anopheles* mosquito takes approximately 7–10 days, from the time of egg laying to the emergence of a new adult mosquito, and therefore a habitat must exist for at least 7–10 days in order to provide a new generation of mosquitoes [Depinay et al., 2004]. By decreasing the pool persistence time, the aim was to ensure that the pool existed for less than 7 days and therefore could not become a productive breeding habitat.

[23] Leveling of the topographic depression where the pool forms was simulated by altering the input domain DEM. In the vicinity of the pool basin, the DEM was edited to decrease the maximum depth of the depression by varying degrees. The existing topography has a minimum elevation of 209.3 m (relative to mean sea level) in the center of the pool.

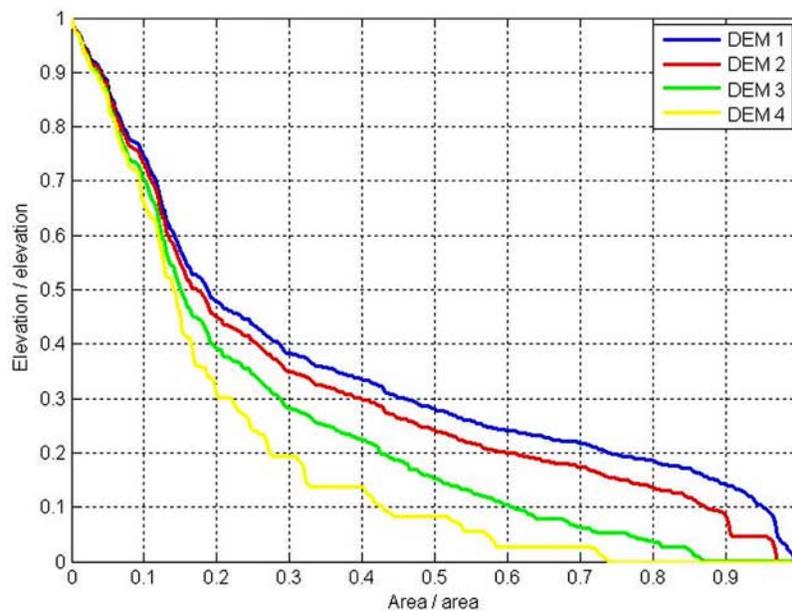


Figure 5. Hypsometric curves showing how the pool basin was altered in the simulations of the leveling intervention. The curves show the distribution of elevation within the basin as a function of the area of the basin under each digital elevation model (DEM). With increasing degrees of leveling, the basin becomes flatter such that an increasing area of the basin has a similar elevation.

[24] Model simulations were undertaken using four different DEMs: the original existing topography (DEM 1), simulated leveling to raise the base elevation by 15 cm in the center of the pool (minimum elevation 209.45 m, DEM 2), simulated leveling to raise the base elevation by 35 cm (minimum elevation 209.65 m, DEM 3), and simulated leveling to raise the base elevation by 45 cm (minimum elevation 209.75 m, DEM 4). The simulated changes in elevation can be shown through hypsometric curves, as in Figure 5. The hypsometric curves show, for each DEM, the distribution of elevation within the basin as a function of the area of the basin, normalized to the difference between maximum and minimum elevations in each DEM. With increasing degrees of leveling, the basin becomes flatter such that an increasing area of the basin has a similar elevation. The objective of this method was to create pools with greater area and shallower depth to increase the flux of water out of the basin by providing more surface area for infiltration and evaporation processes to act on.

[25] These simulations mimic a process where in reality soil would be excavated from around the edges of the pool basin and redistributed to fill in the center of the pool, making the depression shallower and spreading the pool out over a greater area. Leveling of a topographic depression would be technologically simple to undertake in the field, requiring only manual labor resources.

[26] Plowing of the surface soils in the pool basin was simulated by altering the input soil parameters. The model simulates soil moisture and unsaturated zone hydrology with six soil layers. The topsoil layer across the model domain was assigned a thickness of only 10 mm to represent the thin crusted layer of low permeability that is typical of this region. This surface layer was assigned a saturated hydraulic conductivity of 2.2 mm/h across most of the domain, which is appropriate for fine sands and unconsolidated clays such as t that comprise this surface

crust. Within topographic depressions where pools form, fine sediment accumulates and over time reduces the surface permeability even further. Therefore, locations where pools are known to form regularly around Banizoumbou were assigned a slightly lower saturated hydraulic conductivity of 1.8 mm/h. Beneath the surface layer, the sands in the region around Banizoumbou are of medium coarseness, well-sorted, and are fairly homogeneous. Therefore all the soil layers in the model below the surface layer were assigned a saturated hydraulic conductivity of 4.3 mm/h, an appropriate rate for these sorts of sands. To simulate plowing, the saturated hydraulic conductivity of the surface layer within the 60 m × 40 m area of the pool basin used in this investigation was increased to 4.3 mm/h, the same as the underlying soil layers. Saturated hydraulic conductivities were determined through model calibration, optimizing the dynamics of the pool under investigation to match observations of its behavior. The objective of this method was to retain the existing geometry of the pool basin but increase the flux of water out of the basin by increasing the infiltration rate.

[27] These simulations mimic the process of hoeing to break up and remove the surface crust layer, exposing the more permeable underlying sands. This technique is currently used by the residents of Banizoumbou on their millet fields during the rainy season to remove weeds and allow rainfall to penetrate to the crop roots. This technique would therefore also be easy to implement by residents and could be achieved by turning over the surface of the pool basin with the same tools used in the millet fields.

[28] In total, six simulations were carried out for each of the 3 years: (1) base case with existing conditions; (2) altered DEM to simulate leveling – DEM 2; (3) altered DEM to simulate leveling – DEM 3; (4) altered DEM to simulate leveling – DEM 4; (5) altered soil surface properties to

Table 1. Water Balance Results 2005

	Total Volume ^a (m ³)	Fraction Infiltrated (%)	Fraction Evaporated (%)	Fraction Overflowed (%)	Maximum Pool Volume (m ³)
Simulation 1 (base case DEM 1)	25,465	74	7	19	1030
Simulation 2 (DEM 2)	25,245	73	7	20	957
Simulation 3 (DEM 3)	24,469	70	6	24	725
Simulation 4 (DEM 4)	23,100	59	5	36	273
Simulation 5 (DEM 1 with plowing)	25,007	76	7	17	1008
Simulation 6 (DEM 3 with plowing)	24,760	73	6	21	713

^aThis volume represents the total volume of runoff that is routed through the pool basin during the simulation period, including both water that is dissipated via infiltration and evaporation within the basin and runoff that flows through the basin and exits as overflow. DEM, digital elevation model.

simulate plowing with DEM 1; and (6) altered soil surface properties to simulate plowing with DEM 3.

6. Results

6.1. Water Balance Analysis

[29] A water balance analysis was conducted on the pool for each simulation period of 2005, 2006 and 2007. The water balance analysis was used to determine (1) how pool water loss mechanisms differed between the interventions; (2) which of the loss mechanisms (evaporation and infiltration) was dominant; and (3) the maximum volume of water that can be contained within the pool basin before it overflows and causes downstream flooding, which will be referred to as the maximum pool volume.

[30] Table 1 shows summary water balance results from the 2005 simulations. Table 1 shows for each simulation: the total volume of water that was routed through the pool basin over the length of the simulation period; the fraction of that total volume that was lost via infiltration; the fraction of the total volume that was lost via evaporation; the fraction of the total volume that left the basin via overflow to downstream areas; and the maximum pool volume. The results from 2006 and 2007 are not shown but were similar to 2005.

[31] Table 1 shows that pool dissipation is dominated by infiltration for all simulations. Infiltration accounts for dissipation of 59–76% of the total volume of water that is routed through the pool basin in 2005. With regard to dissipation of the contained pool volume, i.e., ignoring overflow from the pool basin, infiltration accounts for approximately 90% of the pool dissipation, with evaporation dissipating the remaining 10% of the contained pool volume. This is consistent with the relative dominance of infiltration processes compared to evaporation processes as documented by *Desconnets et al.* [1997] for other similar pools in the region. Table 1 also shows that of all the water that is routed through the pool basin in any of the simulations, about 20% is not dissipated on site but overflows to other basins, indicating the pool basin area is not a global topographic minimum but only a local minimum. The maximum pool volume decreases with simulated leveling (i.e., decreases from DEM 1 to DEM 4) but is not significantly altered by simulated plowing.

6.2. Intervention Effects on Pool Persistence Time

[32] The effect of each intervention on the pool persistence time was evaluated by looking at the discrete pooling

events that occurred in each simulation. A pooling event was defined as the length of time that the model simulated water to continuously exist in the center of the pool. If the model recorded no water in the center (deepest part) of the pool, such that it completely dried out, then the next time that water was simulated in the pool center became a new pooling event. The length of each discrete pooling event in each simulation was defined as the pool persistence time for that event.

[33] The effect of leveling on the persistence time of the pool during 2005, 2006, and 2007 can be seen in Figure 6 as a function of the maximum water depth attained by the pool during that pooling event and in Figure 7 as a function of the corresponding maximum areal extent of the pool. Figures 6 and 7 are shown on a log linear scale. Table 2 summarizes the effects of the different leveling simulations on number of discrete pooling events, average persistence time, average depth, average area, and the rainfall interstorm period.

[34] Figures 6 and 7 and Table 2 show that leveling increases the number of discrete pooling events, such that the pool dries out completely many more times throughout the simulation period. Table 2 shows that the average depth and average area per pooling event are inversely related and that the persistence time decreases significantly with decreasing pool depth and increasing pool area. Figure 6 shows that there is a nonlinear relationship between the persistence time of a pooling event and the maximum water depth attained in the pool during that event. The maximum water depth with the existing topography (DEM 1) is about 45 cm, while the maximum water depth with the shallowest topography (DEM 4) is about 12 cm. With the existing topography (DEM 1), the pool persists for up to 12 days at a time. With DEM 4, the pool does not persist for longer than about 1 day at a time before drying out completely during the simulation period. Figure 7 shows that the shallower water depths attained with leveling create pools with larger areal extents, such that the pool surface area generally increases from DEM 1 to DEM 4. The effect is particularly pronounced for pools with persistence times of between 1 and 5 days.

[35] The effect of plowing on the persistence time of the pool during the 2005, 2006, and 2007 simulations can be seen in Figure 8 as a function of the maximum water depth attained by the pool during that pooling event and in Figure 9 as a function of the maximum areal extent of the pool. Figures 8 and 9 are shown on a log linear scale. Table 2 summarizes the effects of the different plowing simulations

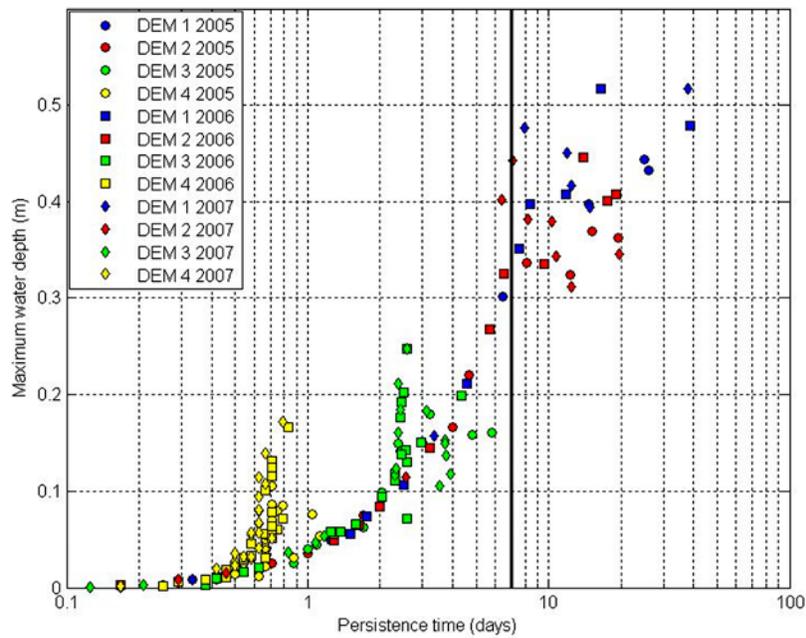


Figure 6. Comparison of persistence time and maximum pool water depth for each of the four DEMs from the leveling intervention in 2005, 2006, and 2007. The black vertical line marks the lower bound of the critical time threshold (7 days) for development of a productive mosquito-breeding habitat.

on number of discrete pooling events, average persistence time, average depth, average area, and the rainfall interstorm period.

[36] Figures 8 and 9 and Table 2 show that plowing has a similar effect to leveling, by increasing the number of discrete pooling events compared with the existing soil parameters. Table 2 shows that plowing leads to pools with similar average depth and average area, compared to simulations with the same DEM, but with significantly reduced

persistence times. The effect is most pronounced when comparing the existing situation (DEM 1) with the same topography and surface plowing (“DEM 1 high inf”). With the existing soil parameters, the maximum persistence time of a pooling event is about 12 days. This reduces to about 8 days if surface plowing is undertaken. Once leveling is implemented (DEM 3), the addition of surface plowing (“DEM 3 high inf”) reduces the maximum persistence time of a pooling event from about 6 days to about 4 days.

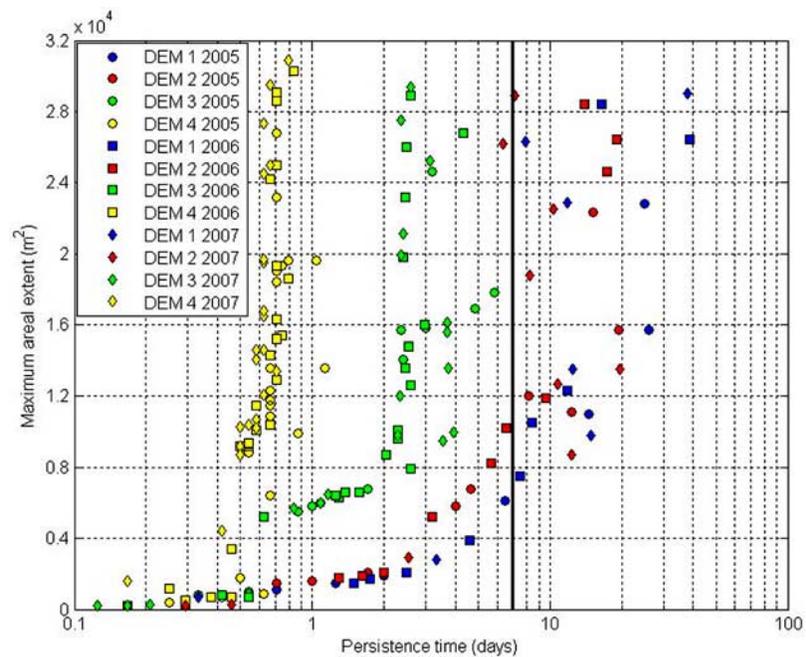


Figure 7. Comparison of persistence time and maximum areal extent for each of the four DEMs from the leveling intervention in 2005, 2006, and 2007. The black vertical line marks the lower bound of the critical time threshold (7 days) for development of a productive mosquito-breeding habitat.

Table 2. Summary Pool Formation Characteristics 2005

	Discrete Pooling Events	Average Pool Depth ^a (m)	Average Pool Area ^b (m ²)	Average Persistence Time ^c (days)	Average Interstorm Period ^d (days)
Simulation 1 (base case DEM 1)	7	0.125	1974	10.9	2.9
Simulation 2 (DEM 2)	10	0.089	2230	6.7	2.9
Simulation 3 (DEM 3)	16	0.036	3896	2.0	2.9
Simulation 4 (DEM 4)	22	0.014	4052	0.7	2.9
Simulation 5 (DEM 1 with plowing)	15	0.133	2047	3.2	2.9
Simulation 6 (DEM 3 with plowing)	18	0.036	3877	1.3	2.9

^aThe average pool depth was calculated as the mean depth of water in the pool basin during each discrete pooling event over the simulation period.

^bThe average pool area was calculated as the mean area of water in the pool basin during each discrete pooling event over the simulation period.

^cThe average persistence time was calculated as the mean persistence time of all discrete pooling events over the simulation period.

^dThe average interstorm period was calculated as the mean length of time between rainfall events, where independent events were taken to be rainfall that occurred 6 h or more apart.

Figures 8 and 9 also show that surface plowing has little impact on either the maximum water depth attained within the pool or the areal extent of the pool, with the maximum water depth and areal extent for both DEM 1 and DEM 3 approximately the same regardless of whether or not plowing was implemented.

7. Discussion

[37] The results show that the simulated leveling intervention has significant effects on the pool water balance. As the degree of leveling increases from DEM 1 to DEM 4, the total volume of water that is routed through the pool basin area over the simulation period decreases. This is to be expected since the leveling process reduces the maximum

pool volume. If a pool basin were located at the lowest topographic point within the modeling domain, even after leveling, then changes to the elevation would not alter the volume of water routed into the basin. However, the pool basin used in this case study is not located in such a global topographic minimum. Therefore, when leveling is undertaken and the basin elevation is raised, it becomes higher than other locations within the domain that previously would have been up-gradient from the basin but become downgradient after leveling. Table 1 shows that the fraction of the total volume that is dissipated within the pool basin through infiltration and evaporation is decreased with leveling, while the fraction of water that is lost via overflow is increased. Therefore the results show that leveling redis-

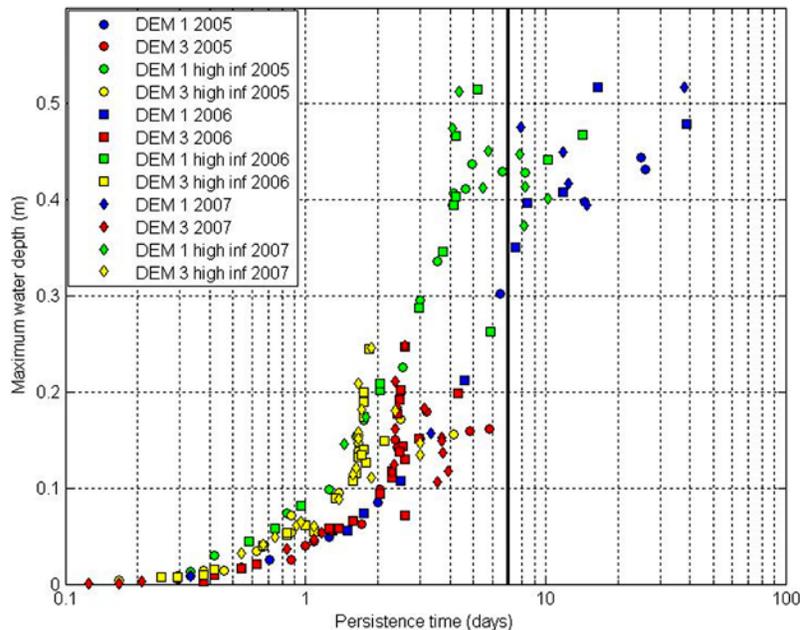


Figure 8. Comparison of persistence time and maximum pool water depth for the surface plowing scenarios in 2005, 2006, and 2007. The existing situation is shown by “DEM 1,” the existing topography with surface plowing is shown by “DEM 1 high inf,” leveled topography is shown by “DEM 3,” and leveling plus surface plowing is shown by “DEM 3 high inf.” The black vertical line marks the lower bound of the cr time threshold (7 days) for development of a productive mosquito-breeding habitat.

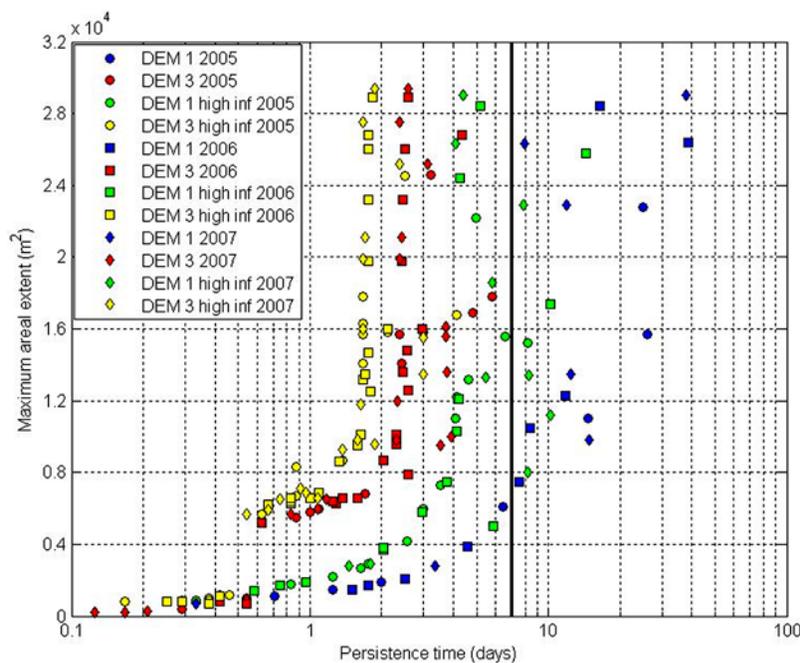


Figure 9. Comparison of persistence time and maximum areal extent for the surface plowing scenarios in 2005, 2006, and 2007. The black vertical line marks the lower bound of the critical time threshold (7 days) for development of a productive mosquito-breeding habitat.

tributes surface runoff such that some of the water that would have dissipated through the pool basin is moved to other locations.

[38] The results show that leveling can dramatically reduce the pool persistence time. This would in turn increase the amount of time that the area is dry, thereby leading to death of larvae and pupae when the pool dries out and reducing the availability of breeding habitat. All of the pool formations that resulted from using DEM 3 and DEM 4 were at or below the critical time for breeding habitat establishment of 7–10 days. This theoretically indicates that if the pool were to be leveled to the extent represented by either of these scenarios and maintained at that level, it could not become a viable breeding habitat for *Anopheles gambiae s.l.* mosquitoes.

[39] However, leveling also increased the volume of overflow. The overflow would create runoff to downstream areas, which could potentially create new breeding habitats or cause nuisance flooding of crops or property. Therefore, the leveling intervention would have to be undertaken with careful consideration of a balance between decreasing pool persistence time and minimizing overflow. Leveling might therefore be a better option for smaller pools, for which increased flooding extent would not cause significant problems, or for cases where the increase in overflow could be managed to avoid downstream problems.

[40] The change in persistence time due to leveling appears to be dramatic considering the relatively small changes in water balance that are shown in Table 1. This outcome can be understood in terms of the relative dominance of infiltration in dissipating the pool volume. Table 1 indicates that leveling has the effect of increasing the ratio of overflow volume to infiltration volume. However, even under the most severe leveling scenario (DEM 4), infiltration processes still account for the vast majority of the pool

dissipation. Therefore small changes to the infiltration dynamics of the pool have a greater impact on the pool persistence time than small changes to the overflow volume.

[41] The simulated plowing intervention also affects the pool water balance. The results show that, relative to simulations with the same topography but existing soil parameters, the plowing intervention increases the fraction of the total water volume that infiltrates within the pool basin. This can be attributed to the increase in surface soil hydraulic conductivity. Plowing also decreases the fraction of the total water volume that is lost via overflow to downstream locations. The maximum pool volume and the fraction of water that is dissipated through evaporation are relatively unchanged by plowing. Plowing therefore has the effect of retaining the geometry of the existing pool basin but enhancing on-site dissipation by increasing the infiltration volume, and thereby shifting some of the pool dissipation from overflow to on-site infiltration.

[42] As with the leveling technique, the plowing intervention appears to dramatically alter the persistence time of the pool with relatively small changes to the water balance. The plowing technique by itself could potentially reduce the persistence time of the pool to below the critical time period required for establishment of a breeding habitat and completion of a mosquito development cycle. This again can be understood in terms of the dominance of infiltration as a dissipation process: plowing increases the infiltration rate within the basin, thereby enhancing this loss mechanism. Because of the dominance of infiltration as a loss mechanism for the pool, small changes to the infiltration rate lead to dramatic changes to the pool persistence time.

[43] Although plowing and leveling work by changing the pool water balance in different ways, they have similar significant effects on the persistence time of the pool. However, when they are implemented simultaneously, the

results indicate that there is little additional improvement over the gains from implementing only one intervention. This suggests that efforts should be directed toward carrying out only one of these interventions at a given location and not both, in order to allocate time and resources optimally.

[44] The results from this case study investigation could be used to formulate some general management principles for ephemeral pools in Sahelian Niger. Given that infiltration processes are the dominant method of runoff dissipation, and are much more rapid than evaporation processes in this region during the rainy season, it is recommended that efforts to alter the hydrology of such pools should focus on increasing the infiltrability of pools, subject to two conditions: (1) not causing downstream problems due to increasing overflow; and (2) reducing the persistence time of the pool to less than the breeding habitat establishment time where possible.

[45] Changes to the pool persistence time can be considered in relation to the rainfall interstorm period. The rainfall interstorm period is the length of time between the end of one rainfall event and the start of the next rainfall event. The average rainfall interstorm period for the 2005 rainy season was just under 3 days, as shown in Table 2. If a pool persists for as long as or longer than the interstorm period, it will always be present during the rainy season and remain available for utilization by mosquitoes as a breeding habitat. Framed in this way, the topography represented by DEM 1 and DEM 2 creates pools with an average persistence time that is greater than the average interstorm period, such that there are very few discrete pooling events. However, if the pool hydrology can be altered such that the persistence time is less than the interstorm period, such as with DEM 3 or DEM 4, it will dry out between rainfall events and become less available for utilization as a breeding habitat. Some knowledge of the rainfall characteristics in a region, including the interstorm period, would therefore be helpful in optimizing changes to pool hydrology.

[46] *Shaman and Day* [2007] showed that the timing of rainfall events can be very important for modulating adult mosquito populations, with rainfall events spaced near the natural frequency of the ideal mosquito reproductive cycle allowing the population to grow at its most efficient. The effect of rainfall on adult mosquito behavior was not explored in this study. However, it is possible that the environmental management methods investigated in this study could help in reducing any amplifying effects that the timing of rainfall events has on mosquito population growth, by limiting the availability of breeding habitats to adults that may exhibit increased flight activity and host-seeking behavior due to rainfall.

[47] There are costs and benefits to both of the techniques investigated in this study. Advantages of these techniques are that they can be easily undertaken by village residents with minimal equipment and do not require a great deal of prior knowledge: residents could simply target locations where they observe pools to form and visually assess the degree of slope in a topographic depression or the extent or surface permeability (easy to assess by the presence or absence of surface soil crusting). However, surface plowing and leveling are likely to require regular maintenance throughout the rainy season, as surfaces harden, erode, or accumulate sediment after rainfall events. Regular time

would therefore have to be devoted to maintaining these interventions during the rainy season, which is when men are required to be working in the fields and tending to rain-fed crops, and thus may present a time conflict. The appropriateness of these techniques to a given village or even a given pool would therefore have to be assessed on a case-by-case basis.

[48] This study focused on numerical simulations of environmental management methods to demonstrate the potential utility of hydrologic models in designing malaria control programs. Future work to confirm the efficacy of the methods investigated here would include a field validation study. This could be undertaken relatively simply by implementing the leveling and plowing techniques on one or more of the pools commonly found around Banizoumbou village, including the one used in the case study presented here. The simulations conducted in this investigation could be used as the initial design for the field experiments. The field validation study could also be used to determine the logistics of how such a management program could be carried out in practice in communities like Banizoumbou, for example, continuation of maintenance activities. Following a field validation study, the next step in scaling up the results of this investigation would involve a more global model for assessment of all relevant depressions within a community, including assessment of how the management of one water body affects others in the near vicinity.

[49] In generalizing the results of this investigation to other communities in the region, it should be noted that application of a model like HYDREMATS cannot be undertaken without accompanying field studies to ascertain local environmental conditions. Much depends on the heterogeneity of the local environment, especially substratum permeability, from one site to another, and thus the model would need to be recalibrated for a new location. The characteristics of individual water pools should also be known, including the contribution of a pool to adult mosquito emergence (and therefore malaria transmission), utility by local residents, and potential impact of any modifications on downstream locations. Satellite imagery could potentially be used to assist in scaling up to other communities in the region. *Mushinzimana et al.* [2006] demonstrate the potential usefulness of remote sensing for identifying anopheline mosquito larval habitats in western Kenyan highlands. A similar method could be used to help in the identification of the most appropriate locations for interventions.

8. Conclusions

[50] Hydrologic controls on the persistence time of mosquito-breeding pools can be used to regulate mosquito emergence and significantly impact the mosquito development cycle. We demonstrate in this investigation that hydrologic modeling can effectively be used for screening of environmental management methods for malaria vector control, to determine a priori which methods would be most suitable in a given context.

[51] We demonstrate in this study that environmental management methods can be efficacious in Sahelian Niger for reducing the availability of mosquito-breeding habitat and reducing pool persistence times to inhibit mosquito development. The results showed that both leveling and

surface plowing techniques can reduce pool persistence times. Leveling spreads out the pool over a larger surface area to enhance infiltration processes. Leveling can potentially cause problems downstream by increasing overflow from the pool basin and therefore needs to be carefully considered in a given setting. Plowing increases the dissipation of water that occurs locally within the pool basin and thereby reduces overflow. Both techniques have the potential to be efficacious in reducing the availability of a given water body for establishment as a mosquito-breeding habitat.

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