The Potential for Environmental Management to Contribute to Malaria Vector Control in Western Niger

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ABSTRACT

This thesis investigated the potential for environmental management techniques to contribute to malaria vector control in Niger, with a case study on Banizoumbou village in western Niger. Numerical modeling was used to simulate habitat modifications in the form of leveling a topographic depression, ploughing the land surface to enhance infiltration and providing barriers to surface runoff on hillslopes. The hydrologic model described by Bomblies *et al.* (2008) was used for the modeling investigation, calibrated using environmental observations obtained in Banizoumbou for the years 2005, 2006 and 2007. The modeling investigation showed that leveling of topographic depressions could reduce the persistence time of a pool to less than the time needed for establishment of mosquito breeding, approximately 7 days. Increasing the surface soil permeability by ploughing also reduced the persistence time of the pool but was not as effective as leveling. Therefore leveling is the recommended intervention for pools of a small to intermediate size, while ploughing would be recommended for large pools where leveling would require too much work to implement. Interception of hillslope runoff using a barrier was demonstrated to be the most effective way to prevent a pool from becoming breeding habitat. However, this method has the most risk of creating unintended downstream impacts and therefore must be used with extreme caution.

A field trial was also undertaken during July to September 2007 in Banizoumbou to investigate the efficacy of neem seeds as a larvicide and to reduce adult emergence from breeding pools. The neem field trial showed that twice-weekly applications of neem seed powder to known breeding habitats of Anopheles larvae in 2007 resulted in 49% fewer adult female *Anopheles gambiae s.l.* mosquitoes in Banizoumbou compared with previous captures under similar environmental conditions and with similar habitat characteristics in 2005 and 2006. The results of the neem field trial suggest that neem seeds could provide an appropriate, sustainable larvicide for the malaria vector *An. gambiae s.l.* in the Sahel region of Niger and adjacent areas having similar environmental characteristics and vector dynamics.

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1. Introduction

1.1 Background

Malaria continues to place a large social and economic burden on African communities. 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). 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 and are not dependent on such site-specific knowledge as is required for larval control methods (Carter *et al.* 2000; World Health Organization 2006). Integrated vector management programs, employing a variety of tools for targeting both adult and sub-adult vector stages, may provide the greatest chance for success in reducing malaria transmission rates (Walker and Lynch 2007). Methods that target the larval stages of mosquitoes have the potential to be effective, low-cost and with low environmental impact (World Health Organization 1995; Killeen *et al.* 2002; Konradsen *et al.* 2004; Gu and Novak 2005; Utzinger *et al.* 2006). If modern-day larval control 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 international donors of malaria control programs.

1.2 Research Questions

The aim of this thesis was to investigate the potential for environmental management to contribute to malaria vector control in Niger, with a case study on Banizoumbou village in western Niger. The investigation focused on methods that target the larval stages of *Anopheles gambiae s.l.*, the major local malaria vector in western Niger, by either preventing larval habitat from forming or inhibiting adult emergence from the larval stage.

After a detailed discussion of the literature on environmental management methods used for malaria control in Chapter 2, a numerical modeling investigation is presented in Chapter 3. This investigation was used to simulate habitat modifications in the form of leveling topographic depressions where breeding pools typically form, ploughing the land surface to enhance infiltration of breeding pools and providing barriers to surface runoff to reduce the size of breeding pools. Chapter 4 describes a field trial that was undertaken to investigate the efficacy of neem seeds as a larvicide and to reduce adult emergence from breeding pools. All of the environmental management methods investigated in this study were chosen for their suitability to the local environmental conditions and vector dynamics, because they are low-cost and require very little materials or resources, and because they could be carried out by the residents of Banizoumbou in the long-term in a sustainable manner.

1.3 Study Location

This study focused on Banizoumbou village, located in western Niger, approximately 60 km northeast of the capital Niamey (see Figure 1), and home to approximately 1000 people. Banizoumbou is representative of the many small villages in Sahelian western Niger and the Eltahir Research Group has monitored environmental variables and mosquito abundance in this village since June 2005. Banizoumbou is located in a semi-arid landscape with gently sloping topography and savannah vegetation cover in the surrounding areas. A large portion of the land immediately adjacent to the village is cultivated with millet fields. The shallow groundwater lies approximately 25-30 m below the ground surface in the village and provides the only source of water for the residents.

During a rainy season that extends roughly from May to early October and peaks in August, many ephemeral pools form within and around the village in topographic low points. These pools do not form complex aquatic ecosystems and are not utilized by the residents. However, they do provide ideal breeding habitat for *Anopheles gambiae s.l.* mosquitoes, the primary malaria vector in the area, and hence the onset of the rains typically brings a substantial increase in mosquito populations and malaria transmission. There is only one permanent pool of surface water in the village; it is used primarily for cattle watering and is not used by the people. Figure 1 shows an aerial photograph of Banizoumbou village. The blue circles indicate the locations of pools that form during the rainy season and have been observed to provide productive habitat for mosquito breeding. The orange diamonds indicate locations where mosquito light traps have been deployed since June 2005. The permanent pool can be seen in the northeastern corner of the photograph.

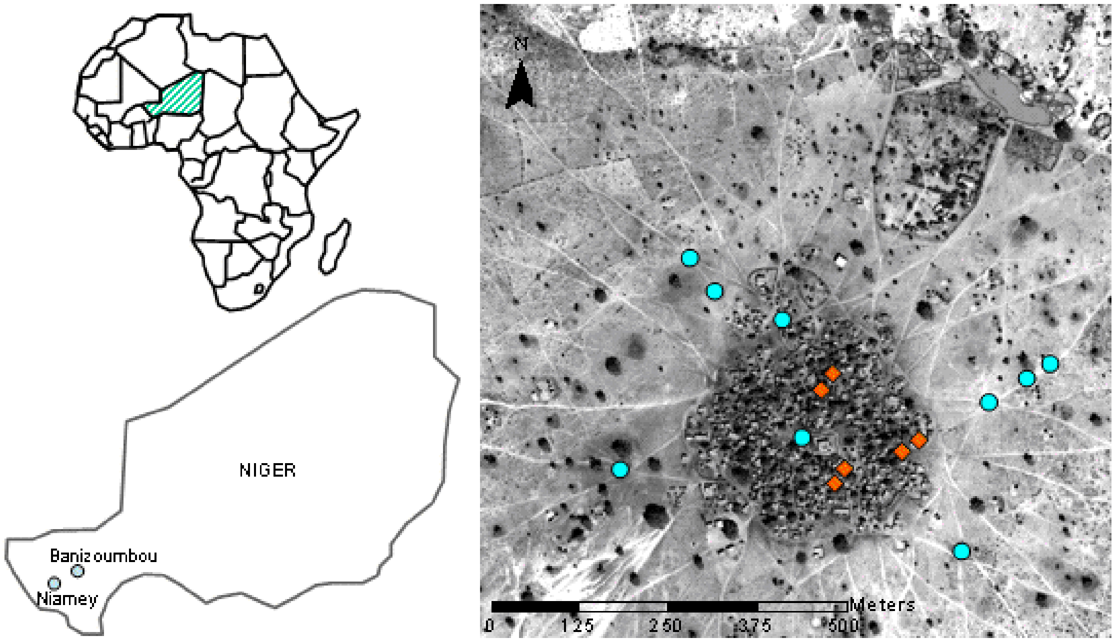

Figure 1: Location of Banizoumbou village. Aerial photograph of Banizoumbou is a Quickbird image taken in January 2003 (copyright DigitalGlobe Incorporated 2005). Blue circles show locations where known *Anopheles gambiae s.l.* breeding habitats form during the rainy season. Orange diamonds show locations where mosquito traps have been deployed by the Eltahir Research Group since June 2005.

2. Literature Review

2.1 Environmental Management

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 1982). Environmental modification measures include drainage, leveling land, filling depressions, contouring reservoirs, modifying river boundaries, lining canals to prevent seepage and constructing hydraulic structures to prevent stagnation, such as weirs. In an urban setting, modification options also include building drains and storm drains, modifying house designs with regard to gutters and roof drains, modifying irrigation schemes, safe practices for storage of domestic water, and installing wastewater management facilities (Prüss-Üstün and Corvalán 2006). Environmental manipulation methods include vegetation management, safe storage of domestic water, managing peridomestic waste (Prüss-Üstün and Corvalán 2007), irrigation management and introduction of larvivorous fish (United States Agency for International Development 2007). The choice of technique depends strongly on the local malaria vector species ecology and environmental conditions (Walker and Lynch 2007).

Conventional understanding of vectorial capacity holds that survival rate of adult vectors is a more significant control on malaria control than population abundance, and hence interventions are typically targeted at reducing adult female mosquitoes. A different theory to the conventional wisdom is that sub-adult controls have the opportunity to be efficacious because they target individuals in relatively confined habitats that have limited mobility, rendering them vulnerable to extermination (Killeen *et al*. 2002). Killeen *et al*. (2002) argue that adult mosquitoes have proved extremely capable of adapting to avoid interventions such as bed nets, for example by selecting for individuals that feed earlier in the evening or outside. In contrast, sub-adult individuals have limited opportunities to develop adaptations to interventions, particularly in the case of habitat removal.

Successes using environmental management

Environmental management techniques have historically been used as effective methods to reduce or prevent malaria transmission (for example: Soper and Wilson 1943; Shousha 1948). A review of 40 studies that emphasized environmental management techniques was undertaken by Keiser *et al*. (2005). Of the 40 studies reviewed, 34 were undertaken prior to the Global Malaria Eradication Campaign (1955-1969), which mainly relied on indoor residual spraying with dichlorodiphenyltrichloroethane (DDT). Environmental modification (measures aiming to create a permanent or long-lasting effect on land, water, or vegetation to reduce vector habitats) was the central feature in the majority (27) of the cases studied, environmental manipulation (methods creating temporarily unfavorable conditions for the vector) was the central feature in 4 cases, and 9 cases quantified the effect of modifications of human habitation. In 16 of the 27 studies that focused on environmental modification, the risk ratio for malaria was reduced by 88% and in 8 of the studies that focused on human habitation modification, the risk ratio for malaria was reduced by 79.5% (Keiser *et al*. 2005). This review indicates that environmental management techniques can potentially be extremely effective for reducing malaria transmission.

More recent investigations into environmental management suggest that it could still today be an effective way to target malaria vectors. A recent field investigation was undertaken by Yohannes *et al*. (2005) into the effectiveness of environmental management for control of *Anopheles arabiensis* in Ethiopia. Techniques were focused on reducing source populations of mosquitoes that bred in water bodies related to dam construction and irrigation schemes, by filling, draining and shading of habitats. These interventions led to an observed 49% reduction in populations of adult *Anopheles arabiensis* compared with pre-intervention, although no conclusions could be drawn regarding the impact on malaria incidence due to a coincidentally low transmission period (Yohannes *et al*. 2005). Fillinger *et al.* (2008) reported that a community-based larviciding program initiated in Dar es Salaam led to a reduction in malaria transmission by the primary local vector, *Anopheles gambiae s.l.*, by 31% after one year of routine applications. Howard *et al.* (2007) showed that a larvivorous fish species commonly farmed and eaten in western Kenya could also be successfully used as a sustainable malaria control tool. These recent field trials, while isolated case studies at present, suggest that further attention to environmental management methods is warranted.

Modeling tools have also been used to simulate the effect of various kinds of environmental management, including larval control, on vector abundance and malaria transmission. Killeen *et al*. (2004) used a resource availability model to simulate the effect of water management, larvicide application, physical domestic protection and zooprophylaxis on various aspects of malaria transmission, including emergence rate, host availability, habitat availability and entomologic inoculation rate (EIR). The study was focused on a village in Tanzania, using available field data for model calibration purposes, where the local vector is *Anopheles arabiensis*. Larval control achieved linear reductions in malaria transmission, which is consistent with conventional wisdom on the effect of abundance on vectorial capacity. However, it was also noted that not only did hydrologic management reduce biting rate due to the reduced population size, but it also reduced mosquito survival and corresponding sporozoite prevalence because of the increased length of time spent foraging for habitats. All the simulated interventions significantly suppressed transmission but environmental interventions to reduce available habitat were the most efficacious method (Killeen *et al*. 2004).

It is therefore suggested in this thesis that environmental management has the potential to achieve reductions in malaria transmission if used appropriately. 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 (USAID 2007). 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). It is noted that environmental management cannot achieve the same level of household protection as correctly implemented insecticide treated bed nets (ITNs) or indoor residual spraying (IRS), but it may play a synergistic role in community-wide protection through source reduction.

Cost effectiveness of environmental management

Despite historic successes with environmental management, it is rarely a part of modern day malaria control programs, especially in Africa (Walker and Lynch 2007). Economic inefficiency is often cited as a reason for excluding environmental management from modern day malaria control programs. However, data on the cost-effectiveness of environmental management programs are scarce and comparative economic analyses of these programs with current approaches, such as ITNs and IRS, are few.

Utzinger *et al*. (2001) undertook a detailed cost-effectiveness analysis to compare environmental management measures used successfully at the Roan Antelope copper mine in northern Zambia, between 1929 and 1949, with current, widely used methods. (This program was included as one of the successes in the study by Keiser *et al*., 2005.) The program implemented in Zambia was estimated to have averted 4173 deaths from malaria and 161,205 malaria cases. When converted to disability adjusted life years (DALYs), the environmental management program was estimated to have averted 2439-3172 DALYs during its initial 3-5 year start up period, increasing to 10,976 DALYs for the period of 1947-1949 (Utzinger *et al*. 2006). Initial capital investment was estimated at an equivalent of US$167 per person, with annual maintenance costs estimated at US$5.2-23.40 per person (Utzinger *et al*. 2006). The estimated cost per averted death was US$858 and the cost per averted malaria case was US$22.20. Annual costs per person decreased every year until the end of the program (Utzinger *et al*. 2006). The estimated costs for this program compare favorably with costs estimated more recently for ITN distribution programs in Africa. The estimated cost of an averted death from malaria due to ITNs has been estimated at between US$219 and US$2958 in The Gambia, Ghana, Kenya and South Africa, and the cost of an averted malaria case using ITNs has been estimated as US$15.75 in The Gambia (Utzinger *et al*. 2006).

Fillinger and Lindsay (2006) showed that a microbial larviciding program in rural western Kenya was successful in reducing *Anopheles* larval density by 95% and human exposure to biting by 92%. The estimated cost of providing this level of protection to the residents of the study area was less than US$0.90 per person per year. By contrast, a long-lasting ITN costs approximately $5 to manufacture and is effective for about 5 years with correct usage (Teklehaimanot *et al.* 2007). With about 80% coverage needed to provide community-level protection, ITN costs translate to about US$0.80 per person per year if the nets lasted for 5 years. These comparative costs illustrate that environmental management can be as cost effective as other methods currently in favor, although further economic studies of environmental management would be welcomed.

Issues with implementation of environmental management

The primary challenge with successful implementation of environmental management appears to lie in the ability of *Anopheles* mosquitoes to adopt a huge variety of breeding habitats and the inherent requirement for detailed local knowledge of mosquito ecology and environmental conditions.

It is well known that *Anopheles gambiae s.l.* mosquitoes are capable of occupying a diverse range of habitat types, both natural and manmade. As an example, in their study of Mbita, a rural town in western Kenya, Fillinger *et al*. (2004) observed that at any given time 67% of the potential habitats in the town (defined as stagnant water bodies) contained *Anopheles* larvae. This figure rose to 83% during the wet season, which is to be expected as the rains create more water bodies that persist for the full length of a mosquito breeding cycle (Fillinger *et al*. 2004). The breeding sites included lake side and hill side locations, natural and concrete-lined pools, presence and absence of vegetation, permanent and temporary pools, small (2 m^2) and large (75 m^2) pools and depths varying from 1-106 cm. This broad range of habitat characteristics illustrates that potential breeding habitat for malaria vectors cannot be generalized, even within a given township. In highly endemic areas, the implication of this study is that any larval control program would need to be extensive in order to target all potential breeding habitats (Fillinger *et al*. 2004), and thus this sort of program is unlikely to be appropriate for an area of high endemicity.

Gu and Novak (2005) used a population model of mosquitoes to investigate how extensive a larval control program would need to be in order to effect significant changes in malaria prevalence and incidence in low to intermediate transmission areas. The authors simulated scenarios where mosquito habitats had variable productivity and larval control interventions could either be randomly distributed amongst the habitats or targeted towards the most productive ones. 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 entomological inoculation rate (EIR) and a 66% reduction in malaria incidence (Gu and Novak 2005). This work suggests that larval control can have a significant impact on malaria transmission and also that complete coverage of an area is unnecessary to achieve this outcome. It was noted, however, that untargeted (random) larval control interventions had little to no impact on EIR or malaria incidence, illustrating that it is crucial for decisions regarding larval control to be informed with good local knowledge of mosquito breeding sites. The authors also caution that larval control will not be effective in all situations and, as with all things related to the environment, will need to be considered on a site-specific basis.

The studies by Fillinger *et al*. (2004) and Gu and Novak (2005) suggest that larval control programs would be most effective if used in areas of low to intermediate malaria transmission or to target the dry season habitats that permit perennial transmission. Shililu *et al.* (2007) showed that larval control methods in semiarid ecosystems in Eritrea were effective in managing malaria vectors due to the discrete nature of the habitats, which made them easy to identify, map and target for intervention. Dry season habitats are usually easier to identify, well defined and less numerous, making it easier to focus scarce resources. Because these habitats often act as refugia for mosquitoes during harsh dry times, their removal could interrupt the transmission cycle and reduce the potential for wet season proliferation of mosquito populations (Fillinger *et al*. 2004). In contrast to areas of high transmission, areas of low to intermediate transmission do not require full or even majority coverage of potential breeding habitats, reducing the number of target sites and thus required resources (Gu and Novak 2005). Under these conditions then, larval control programs have the potential to affect significant change in malaria transmission and would not be as resource intensive as larval control measures are often assumed to be.

Environmental management-based strategies are by nature locally based and implemented at the community scale, and therefore successful implementation requires detailed knowledge of local scale environmental determinants of malaria transmission and mosquito ecology (Carter *et al*. 2000; Killeen *et al*. 2002). It also requires expertise in design and adaptation of the various techniques of environmental management. Such knowledge is scarcely available in most places in Africa where these sorts of interventions could be useful. Because of the dependence on local knowledge and experience, environmental management programs are generally not transferable between locations but must be determined on a site-specific basis. This has led the WHO to conclude that IRS and ITNs are "more broadly applicable geographically" than environmental management or larval controls, and thus environmental controls are not considered a significant part of the WHO's recommended strategy for malaria vector control (WHO 2006).

One potential method for helping to disseminate the local knowledge that is required is the establishment of partnerships between educational institutions and communities. These sorts of partnerships have been used successfully in the past for managing a variety of vector-borne diseases, including malaria (Mukabana *et al*. 2006). It is also recognized that community-based ecosystem management has achieved success for pollution control and veterinary vector control in many places (Mukabana *et al*. 2006). Therefore it is suggested that an effective way to incorporate environmental management into modern-day integrated malaria vector control programs might be to use community-based methodologies that benefit from the knowledge of educational institutions (Mukabana *et al*. 2006). This approach was shown to work successfully on Rusinga Island, western Kenya, and in Dar es Salaam, Tanzania (Mukabana *et al*. 2006). In these examples, malaria control and surveillance controls were initiated by community groups, who then sought assistance from experts to fill knowledge gaps. It is suggested that a community-driven approach seeking assistance from educational institutions is likely to have more success than an approach initiated by that institution (Mukabana *et al*. 2006).

Another challenge for successful implementation of environmental management programs may be the requirement for a high level of organization of such programs and the need for longevity of activities, in order to see the best results. It was noted in the study by Utzinger *et al.* (2006) that, although the program was successful in reducing malaria from the outset, the greatest benefits were only experienced after 3-5 years of implementation. An environmental management program is likely to be a long-term commitment, not a short-term fix, requiring patience on behalf of receiving communities and determined effort of behalf of those implementing the programs. It was noted that one primary reason for the successful implementation of the environmental management program in Zambia (then Northern Rhodesia) was the strong colonial structure at the time, and consequently the ability to tightly manage interventions (Utzinger *et al.* 2006). This kind of authoritarian control is no longer likely to be either possible or desirable. Capacity building will be critical if environmental management is to be made available as a strategy in more than isolated situations. Because environmental management methods and larval controls do not achieve the same immediate knockdown effect of ITNs and IRS, it may be difficult for people to believe in their effectiveness and invest the required time and labor for implementation.

Governments are typically short of resources and would have limited capacity to carry out widespread implementation of environmental management methods, as they are already unable to disseminate ITNs and treatments where they are needed, particularly in rural areas (Kouyaté *et al.* 2007; Teklehaimanot *et al.* 2007). Educational institutions can play a large role through education of communities about mosquito ecology, in order for communities to take on the role of program implementation using environmental management methods. However, in order for an environmental management program to be sustained by a community, they will likely need to see proof of reduced malaria burden in order to justify prolonged expenditure of valuable resources.

Issues with synthetic insecticide-based strategies

There is no question that methods to target adult mosquitoes using synthetic insecticides, such as ITNs or IRS, are extremely effective methods for controlling malaria. Combined with improved access to case management, these methods have great potential for reducing the malaria burden in Africa (WHO/UNICEF 2003). There are a number of case studies showing the effectiveness of either method in isolation or both used in combination, such as the reductions in malaria morbidity and case fatality in Eritrea after the implementation of both ITNs and IRS in 2000 (Nyarango *et al.* 2006). In 2006, dichlorodiphenyltrichloroethane (DDT) was re-endorsed by the WHO for use only in IRS campaigns in epidemic and endemic areas (its use in the external environment is still prohibited under the 2001 Stockholm Convention), due to its historically proven effectiveness in reducing malaria burden. The re-introduction of DDT could prove extremely beneficial in reducing malaria transmission. However, for many remote rural African communities, lack of access to and cost of established methods such as IRS and ITNs prohibit effective and widespread implementation (Barat *et al*. 2004).

Another problem is that synthetic insecticides suffer from the issue of developing resistance in the target (and sometimes non-target) mosquito populations. For example, on Bioko Island, Equatorial Guinea, where the malaria vectors are *Anopheles gambiae s.s.*, *Anopheles melas* and *Anopheles funestus*, an IRS program was implemented in December 2003. A pyrethroid spray was used initially, which resulted in significant declines in the populations of *Anopheles funestus* and *Anopheles melas*, but no decline was observed in the *Anopheles gambiae s.s.* populations due to the presence of knockdown resistance to pyrethroids in this population (Sharp *et al*. 2007). A carbamate insecticide was introduced in the second round of spraying, and this time significant declines in *Anopheles gambiae s.s.* populations were also observed (Sharp *et al*. 2007).

In another example, annual malaria cases rose significantly during the period 1995-2000 in KwaZulu-Natal province in South Africa, from 4117 cases per year in 1995 to 41786 cases per year in 2000, despite a continued and efficient IRS program using pyrethroid insecticides (Hargreaves *et al*. 2003). This increase in malaria cases was attributed to the reappearance of *Anopheles funestus* with pyrethroid resistance. As a result, DDT was reintroduced in 2000 in parts of KwaZulu-Natal for IRS. A study undertaken in 2002 determined that DDT resistance was emerging in populations in the malaria vectors *Anopheles arabiensis* and *Anopheles quadriannulatus* in the province (Hargreaves *et al*. 2003). If widespread resistance of *Anopheles arabiensis* to DDT were to occur, combined with the existing resistance of *Anopheles funestus* to pyrethroids, this would severely complicate matters and require either a very sophisticated program to target each malaria vector with an effective insecticide or a new methodology altogether.

These results are not isolated events but seem to be typical for insecticide use on African malaria vectors. The message from results such as these is positive but cautionary: insecticides can achieve very positive, immediate outcomes, but their use is always limited by the emergence of resistance in malaria vectors, perpetually requiring new forms to be developed. Coupling of different insecticides or cycling between different varieties, over appropriate timescales, may be ways to overcome the issue of resistance. The WHO recommends the development of newer insecticides and rotation of insecticides between resistant and non-resistant types to overcome the challenge of resistance (WHO 2006).
A new area of research that may also provide an antidote to resistance issues is the synergistic use of repellents and insecticides. A recent study by Pennetier *et al*. (2007) showed that when two repellents, DEET and KBR 3023, were each combined with an organophosphate insecticide, 95% mortality of adult *Anopheles gambiae s.l.* mosquitoes was achieved for more than two months. These results suggest that ITNs impregnated with a combination of a non-pyrethroid insecticide and a repellent could be effective against populations of *Anopheles gambiae s.l.* showing high levels of resistance to individual insecticides. New formulations of both repellents and insecticides, and new ways to combine them synergistically, will continue to be developed. These sorts of methods may prove essential in the future to remain one step ahead of developing resistance in *Anopheles* species and ensure that ITNs, IRS and similar methods remain effective.

Environmental management techniques have an advantage over synthetic insecticide-based programs in that they do not suffer from vector-acquired resistance, and thus provide a long-term effective means of vector control (Konradsen *et al*. 2004). These techniques also have the benefit of providing community protection regardless of individual immunity or protection status, and thus can provide some level of consistent malaria transmission control, particularly in areas of high mosquito or human population flux.

It should be noted that, even if resistance to a particular insecticide develops, the insecticide may still be useful for reducing the force of transmission by reducing the longevity of resistant mosquitoes (Sachs 2002). For this reason, ITNs can remain effective in reducing malaria transmission after local mosquito populations are observed to develop resistance to the insecticide used to impregnate the net.

Future possibilities – harmony of the natural and synthetic?

The WHO report (2006) lists characteristics required for success of each of IRS, ITNs and larval control (environmental management) methods. For IRS and ITNs, the most critical criteria are a non-nomadic population, willingness by the population to use the intervention and ability to organize an effective implementation campaign (which presumably includes the necessary funding for the campaign). For larval control, the critical criteria are the ability to locate breeding sites, selection of appropriate control methods and community participation in implementation. Although the WHO significantly plays down the requirements for implementation of IRS and ITNs, experience over the last decade in various parts of Africa has shown that neither willingness by people to use these methods nor the ability to distribute them are assured quantities, and indeed may be as difficult to achieve as the requirements for larval control. The WHO (2006) acknowledges that in western Africa particularly, IRS has not been used due to a lack of capacity for carrying out an appropriate program, and ITN use has been very low, with a reported less than 2% of children sleeping under ITNs, despite significant efforts by international donors since the Abuja Declaration to distribute ITNs. It would therefore appear that despite its reputation for being the more difficult strategy to implement, environmental management faces challenges only equal in magnitude to those of other methods, and should not be discounted for this reason.

Although malaria control programs are usually developed uniformly for a region or a country, there is increasing evidence that malaria transmission dynamics and prevalence vary on much smaller scales, even down to the village scale (see for example Ye *et al.* 2007). Therefore malaria control programs are likely to be more effective if they are appropriately adapted to suit the ecological and socioeconomic conditions at the scale on which the transmission dynamics varies. Furthermore, this growing evidence of local scale variability suggests that there are likely to be locations where conventional approaches, like ITNs or IRS, are more effective and other locations where environmental management may be more effective. It is also likely that in the majority of circumstances, a combination of strategies will be the most effective approach. An integrated approach to malaria vector management has been advocated by many researchers (for example, Walker and Lynch 2007) and also historically by the WHO (1982).

Given the complexity of malaria transmission dynamics, the number of variables in parasite, vector, environment and human characteristics, and the growing concerns about vector resistance to insecticides, an integrated vector management approach to malaria control seems at least a prudent, if not favored, decision. All available techniques for reducing the burden of malaria have some disadvantage or negative impact, whether it be economic, social or environmental (Sadasivaiah *et al.* 2007; van den Berg and Takken 2007) and no technique on its own provides a panacea for this disease.

Our past and present experiences in trying to combat malaria have taught us that both the vector and the parasite are extremely adaptable, available resources in Africa do not match the magnitude of the problem and cultural norms may inhibit the effectiveness of intervention programs. These issues are not likely to be resolved within a short timeframe. Given past experiences with environmental management successes, the increased availability of data, including remotely sensed data, and increasing sophistication of modeling tools, there is now a great potential to design highly effective environmental management programs. These provide additional weapons in the artillery of malaria control program managers when faced with the aforementioned issues of malaria control. Environmental management methods are not intended to replace other control strategies but rather to be part of an integrated approach to malaria control while reducing human and environmental exposure to insecticides (USAID 2007). The implementation of environmental management is not without cost, but the costs of continuing the current malaria burden on a growing population will surely be higher.

2.2 Neem (Azadirachta indica)

The neem plant, *Azadirachta indica* or Indian lilac, is a member of the Meliaceae (mahogany) family. The plant is thought to have originated on the Indian subcontinent but is now widespread across the tropics and sub-tropics, including much of western Africa (Schmutterer 1995).

Neem is a fast-growing plant. It prefers hot climates with annual rainfall of 400-1200 mm. Mature plants can be tolerant of very high temperatures, as experienced in northern and central Africa, but neem is not frost tolerant. Neem plants are also tolerant of drought and poor, shallow soils, including alkaline and saline soils (Schmutterer 1995). It is thus a very adaptable and hardy plant, which is partly the reason for its degree of spreading and also partly why the trees are so highly prized. Neem trees can grow up to 30 m tall and 2.5 m in girth, with rounded crowns of up to 20 m across (National Academy of Sciences 1992).

The plants are usually evergreen, except under extreme and prolonged drought conditions when they may drop their leaves (Schmutterer 1995). Additionally, neem trees throughout western Africa were noted in the 1980s to be suffering from an outbreak of the insect oriental yellow scale, which defoliates and kills the tree. It is thought that the trees became susceptible to the insect due to the prolonged drought in the Sahel at that time, which placed undue stress on the trees and rendered them vulnerable to pests (National Academy of Sciences 1992). When not placed under such stress, the mature trees are generally repellent to pests (Schmutterer 1995).

Following a flowering season that takes place around June-August in western Africa (Schmutterer 1995 and field observations presented in this thesis), the plant produces olive-shaped fruits that comprise a sweet pulp surrounding a seed kernel. A mature tree can produce approximately 20 kg fruit per year, of which the seed kernel accounts for about 10% of the fruit’s weight (Vir *et al.* 1999).

Traditional uses of neem plants

Neem plants have been prized in Indian cultures for centuries, and have proven extremely useful to other cultures as they have spread across the tropics. Oil extracted from neem seeds can be used to make soaps, cosmetics, lubricants, lamp oils and medicines (National Academy of Sciences 1992). Neem cake, which is made from the whole fruit or from the depulped seed, can be used as a soil additive as it enhances crop growth and neutralizes acidic soils (Foerster and Moser 2000). The leaves of the neem plant can be used as animal feed and to make homeopathic remedies. Twigs broken off the plant can be used for dental hygiene and are effective due to antiseptic properties of the bark (National Academy of Sciences 1992). The wood is used for construction, furniture and fuel. The plant is also an effective windbreak. For example, large areas of the Majjia Valley in southern Niger have been planted with belts of neem trees as part of a CARE project to prevent erosion and desertification (Foerster and Moser 2000). In the hot Sahel, the trees are highly prized for shade. To date, in Africa the primary uses of neem appear to be as timber for fuel and construction and in providing shade (Foerster and Moser 2000).

Neem is considered a particularly appropriate plant for developing countries because it is perennial, extremely hardy, requires little maintenance and most of its parts can be used beneficially (National Academy of Sciences 1992).

Environmental toxicity

The discovery of neem's resistance to pests is generally attributed to Dr Heinrich Schmutterer's work in Sudan in 1959. Schmutterer observed a locust invasion, during which neem plants were the only ones to remain green and untouched by the insects. Upon close investigation, Schmutterer observed that the locusts would settle on the leaves and branches but would not feed. This observation precipitated much research into the properties of neem plants that allow them to repel pests (National Academy of Sciences 1992). Although the full insecticidal properties of neem may not be widely known in western Niger, it has been observed that the villagers use neem wood for construction and as stilts for granaries due to its known ability to resist termite infestations.

The neem seed kernel contains approximately 100 active ingredients, generally belonging to the groups tetranortriterpenoids, diterpenoids, triterpenoids, pentanortriterpenoids and nonterpenoids (Schmutterer 1995). Of these approximately 100 ingredients, azadirachtin is the most well known and most potent compound. It is a tetranortriterpenoid and is present in the seeds at a concentration of about 5 mg/g of kernel (Schmutterer 1995).

Extracts from the seed kernel are known to be toxic to more than 400 species of insects, primarily because it disrupts their growth and reproduction, as well as to nematodes and snails (Schmutterer 1995). The extracts are also toxic to crustaceans, particularly aquatic crustaceans, and have proven to be lethal to some species of fish, such as gambusia and tilapia (National Academy of Sciences 1992). It is generally recommended that neem seed extracts not be used in complex aquatic ecosystems due to the multiple impacts on various species in these ecosystems (National Academy of Sciences 1992). Although birds and bats are often observed eating the neem fruit in eastern Africa without ill effects, trials have shown that the seed kernel can be toxic to birds if consumed (Schmutterer 1995). Neem seed extracts have also shown to be toxic to guinea pigs, rabbits and rats (National Academy of Sciences 1992) and to produce ill effects in dogs, sheep, goats and calves (Schmutterer 1995).

However, the seeds are susceptible to the *Aspergillus flavus* fungus when left in moist air, which is a known carcinogen and produces aflatoxins that can be fatal. It is unclear if the toxic effects observed in guinea pigs and rats were due to the active ingredients in neem or to contamination, perhaps by fungal toxins. For example, trials using neem oil sourced from clean, fungus-free seed kernels found no oral toxicity in rats (National Academy of Sciences 1992). Tests on pure neem seed extracts have shown it is not a carcinogen on its own (Schmutterer 1995). The literature is currently unclear as to the potential confounding of fungal toxins on neem’s observed toxicity.

Tests have shown that neem seed extracts are non-toxic to beneficial species such as spiders, bees, crickets, many bugs and beetles, and are actually beneficial to earthworms (Schmutterer 1995). The United States Environmental Protection Agency (USEPA) has approved approximately 24 neem-based pesticides for use on food and non-food crops. Advice from the USEPA states that “When used as directed on product labels, neither clarified hydrophobic extract of neem oil nor azadirachtin are expected to harm non-target organisms. The substances are found in the environment, where they degrade naturally” (USEPA 2006). The USEPA provides a caveat that neem-based pesticides should not be applied directly to water, presumably because of the effect of azadirachtin on aquatic ecosystems and the ability of water to carry pesticides to non-target locations, and not to use these compounds when honeybees are actively foraging (USEPA 2006).

Neem plants are abundant in Banizoumbou village and the fruits that fall from the plants are left to decompose on the ground where they fall or are carried by wind or animals. Hence the use of neem seeds as an insecticide in this village does not represent the introduction of a new compound to this area. The difference is the location where azadirachtin will be concentrated, from bare ground beneath trees to the pools that provide mosquito habitat, and thus the shift in risk from exposure to neem in this new location. However, these breeding habitats are temporarily formed during the rainy season in topographic low points and do not represent complex aquatic ecosystems. The main risk of applying neem to these pools would appear to be to the domesticated chickens kept by the residents of Banizoumbou village.

Human health impacts of neem

In humans, consumption of neem products appears to be harmless when taken in small quantities. For example, consumption of the fruit pulp and tea made from the neem leaves are current practices in India, Africa and the Caribbean and have no documented ill effects (Schmutterer 1995). Even when sprayed on food crops, the USEPA states that “risks to human health are not expected from use of [azadirachtin-based] active ingredients” (USEPA 2006).

However, consumption of pure neem seed oil can cause diarrhoea, vomiting, metabolic acidosis and encephalopathy. This has resulted in the documented death of children in Malaysia who were administered approximately 5 mL of neem seed oil as a homeopathic remedy (Schmutterer 1995). As mentioned previously, the literature is currently unclear as to whether the toxic effects of neem extracts observed in humans are solely due to the active ingredients in neem or whether they are the result of *Aspergillus flavus* combined with the neem active ingredients. No negative effects have been observed from the use of neem in topical treatments or in dental uses (National Academy of Sciences 1992).

It is known that neem seed extracts have a spermicidal effect and laboratory trials are underway to investigate the potential for neem to be used in a standardized form of birth control (National Academy of Sciences 1992). The major impact of sub-acute or chronic exposure has reported to be a reversible effect on reproduction of both male and female mammals, including humans (Boeke *et al.* 2004).

Hence it appears from the literature that, while ingestion of pure extracts in significant quantities poses a significant risk, incidental ingestion of neem extracts should not pose a significant human health risk. Therefore, with appropriate education about the potential risks of neem and instruction on the required preparation and storage methodologies, it is considered that the use of neem as a mosquito larvicide should not pose a significant risk to local residents.

Documented impacts of neem on mosquitoes

Documented effects on insects include repellence and anti-feeding, deterrence of egg-laying, inhibition of metamorphosis and disruption of growth and reproduction (Schmutterer 1990; National Academy of Sciences 1992; Schmutterer 1995). Extracts from neem seeds are fatal to mosquito larvae and pupae, as they inhibit metamorphosis and thus prevent the emergence of adults when applied to sub-adult mosquitoes. When applied to water containing larvae, the extracts also inhibit larval feeding, causing death within 24 hours (National Academy of Sciences 1992). The extracts also deter feeding and ovipositing of adult mosquitoes. These qualities have led to the development of several commercial mosquito repellants, now available in India and Europe, which are based on neem seed oil (Foerster and Moser 2000). Although there are several commercial neem-based pesticides available, none are currently used in mosquito control programs (Okumu *et al.* 2007).

Recently there have been a number of studies conducted to investigate the particular effects of neem extracts on malaria-transmitting mosquitoes. Exposure of anopheline larvae to undiluted neem oil has resulted in 100% mortality within 12 hours (Aliero 2003). When applied to artificial water bodies every two weeks over a period of three months, emulsified neem oil has been shown to have the same effect on larval mortality and adult density as commonly used synthetic insecticides (Awad and Shimaila 2003). A study using a neem oil formulation on third and fourth stage *Anopheles gambiae s.s.* larvae showed 50% inhibition of adult emergence at a concentration of 6 ppm (Okumu *et al.* 2007). A study using emulsified neem oil showed that within a 3 month period (5 generations), anopheline larvae failed to develop resistance or change their susceptibility to the oil (Awad and Shimaila 2003). Research is ongoing into the potential for neem extracts to provide antimalarial treatments as well as prevention (for example Dhar *et al.* 1998; Udeinya *et al.* 2004; Alshawsh *et al.* 2007; Soh and Benoit-Vical 2007).

A short field trial conducted in Mali applied neem seed powder on known *Anopheles gambiae* breeding sites on a single occasion at the end of the dry season, prior to the commencement of rains (Grunewald and Vollmer 2000). This was reported to lead to an 86% reduction in adult female mosquitoes in the trial village obtained during one subsequent indoor spray catch, while the control village saw sustained numbers of adult mosquitoes (Grunewald and Vollmer 2000). While this trial sounds promising, the trial was too limited to draw conclusions from and the detailed methodology and results remain unpublished.

Resistance of mosquitoes to neem-based compounds is more likely to develop using a refined larvicide based on a single active ingredient, such as azadirachtin, than if the whole seed is used with its multitude of compounds (Mulla and Su 1999; Okumu *et al.* 2007). However, neem does not have a “knock-down” effect on mosquitoes like a synthetic pesticide, and hence will not be very useful in reducing numbers of adult mosquitoes once populations are allowed to establish (National Academy of Sciences 1992). The benefit of neem is that due to its growth and reproduction inhibiting mechanisms, subsequent generations of mosquitoes will be affected such that the long term abundance of mosquitoes should be reduced (Schmutterer 1990).

It is therefore considered that the most effective way to use neem is to apply seed extract to breeding sites when population numbers are low, during the dry season, in order to eradicate as many sub-adults as possible. Once the rainy season commences, regular applications of seed extract should continue to prevent sub-adults from emerging as adults. The efficacy of neem seed extracts has been shown to degrade under exposure to sunlight within 7 days (Schmutterer 1990; Vatandoost and Vaziri 2004) and thus the toxicity is non-persistent in the environment. This provides environmental benefits but also means that regular applications of neem seed extracts would be required to maintain efficacy.

3. Modeling Investigation

The life cycle of mosquitoes of the *Anopheles* genus, the primary malaria vector in western Africa, is fundamentally dependent on local hydrology. The egg, larvae and pupae stages of development are aquatic. Therefore anopheline mosquito abundance and malaria transmission are extremely sensitive to hydrologic variability, in particular fluctuations that affect the availability of suitable aquatic breeding habitats (Shaman and Day 2005). This modeling investigation sought to simulate changes that could be made to the land surface around Banizoumbou village to change the local hydrology, in a way that would negatively impact breeding habitat availability. This investigation has been undertaken as part of a broader project in the Eltahir Research Group investigating the links between hydrology, the environment and malaria transmission.

3.1 Model Description

The modeling investigation uses the hydrology component of the coupled hydrology-entomology model developed by Bomblies *et al.* (2008), which was developed for the mechanistic simulation of local-scale response of malaria transmission to hydrological and climatological determinants in semi-arid, desert fringe environments. The model combines calculation of vertical fluxes of water and heat within a column with determination of distributed overland flow, which allows runoff between grid cells to form the small-scale pools of interest to mosquitoes. The objective of this hydrology model is different from other hydrology models, which may seek to simulate the impacts of large-scale processes such as flooding or drought. The objective of this model is to simulate the location, formation and persistence dynamics of the small-scale pools that form mosquito breeding habitats.

The model explicitly represents the distributed pooled water that constitutes *Anopheles* mosquito breeding habitat as well as the soil moisture that governs the formation of this habitat. The intended primary uses of this model are the evaluation of impacts of climate variability on malaria transmission and the *a priori* evaluation of environmental management-based interventions (Bomblies *et al.* 2008). The modeling investigation presented here represents the first use of this model for the purpose of screening environmental management interventions for malaria control.

The model of Bomblies *et al.* (2008) borrows heavily from the land surface scheme LSX of Pollard and Thomson (1995). The model simulates six soil layers and two vegetation layers for a detailed representation of hydrologic processes in the vertical column. LSX simulates momentum, energy and water fluxes between the vegetation layers, soil and atmosphere. Vegetation type and soil type strongly influence soil moisture profile simulation, and spatially variable soil properties determine roughness in the runoff model. Pool inflows are balanced by a change in volume, infiltration, and evaporation, and levels fluctuate in response to inflows from concentrated runoff. Vertical soil layer thicknesses are assigned to allow simulation of a low-permeability structural crust commonly observed in the Sahel (Bomblies *et al.* 2008).

Meteorological variable inputs for the hydrology model are temperature, relative humidity, wind speed and direction, incoming solar radiation and precipitation. Precipitation at each grid cell is partitioned between runoff and infiltration, based on hortonian runoff processes. The resulting infiltration flux is redistributed in the unsaturated zone with a Richard's equation solver, with soil hydraulic parameters assigned for each layer and grid cell. The soil model subroutine determines unsaturated zone hydraulic conductivity as a function of soil moisture following Campbell's equation. Root zone soil water uptake from transpiration is forced by canopy-level climatic variables (Bomblies *et al.* 2008).

Pool formation is simulated by distributed flow routing. A finite difference solution of a diffusion wave approximation to the St Venant equations determines routed and pooled water for each time step. Run-on onto down-gradient grid cells combines with available precipitation for the next iteration of the unsaturated zone model. In this manner, shallow flow over a spatially variable infiltrating surface is simulated. Flow velocity is represented by Manning's equation with distributed roughness parameter n, which depends on the vegetation cover and soil type at the grid cell, and influences overland flow velocities. The village of Banizoumbou is represented in the model by simulation of inhabitants within residences. A gridded region surrounding human habitation forms the model domain and individual pool locations are predicted using fine-scale topography as hydrology model input (Bomblies *et al.* 2008).

The overland flow module operates at a faster time step than the unsaturated zone model or vegetation canopy energy and water redistribution calculations. The vegetation module tracks evapotranspiration and root zone moisture uptake for the various vegetation types. This interacts with the model's soil water redistribution component, which tracks both soil moisture and temperature in the vertical column. Routed water depths from the overland flow module are updated for infiltration and evapotranspiration losses at each model time step before being returned to the overland flow routing subroutine (Bomblies *et al.* 2008).

3.2 Model Set Up

The model domain consists of a nested grid that spans an area of 2.5 km x 2.5 km, centered on Banizoumbou village, with a total of 100 x 100 grid cells. In the centre of the domain, a 500 m x 500 m area contains grid cells of size 10 m x 10 m. Outside the centre, 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. Figure 2 depicts the model domain, showing the telescopic mesh refinement of the grid cells.

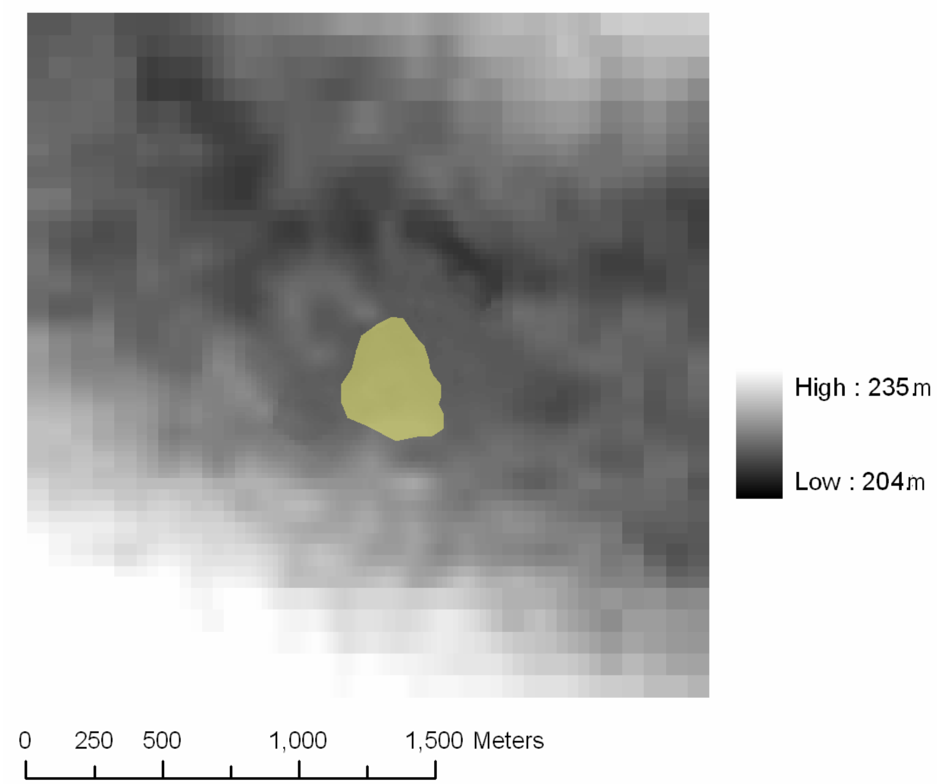

Figure 2: Model domain, showing the village of Banizoumbou in the centre of a 2.5 km x 2.5 km nested grid. The centre contains cells at 10 m resolution and is surrounded by grid cells of 20 m, 40 m and 80 m size at the outside of the domain. The greyscale shading represents the digital elevation model, with the highest points at 235 m above mean sea level in the southwest corner and the lowest points at 204 m to the north of Banizoumbou. (Source: Bomblies *et al.* 2008)

Because of the small inner grid cell size of 10 m, the overland flow module operates at a time step of one second to meet conditions for stability while the unsaturated zone model is stepped at a coarser time step of one hour. Vegetation canopy energy and water redistribution calculations are also performed at one hour time steps.

Vegetation cover and topography over the model domain have been specified using remotely sensed data as described in Bomblies *et al.* (2008). Vegetation cover input is derived from a Landsat-7 multispectral image, using a supervised classification technique. 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). The DEM used in the model simulations is shown in Figure 2.

The six soil layers in the unsaturated soil column have been designated thicknesses of 0.05 m, 0.10 m, 0.10 m, 0.50 m, 0.50 m and 1.0 m respectively, from the surface downwards. The surface layer thickness is small to enable simulation of the surface crust that forms in this region, which has a very low permeability and severely inhibits infiltration over large areas. Beneath the surface crust, the soils around Banizoumbou are observed to be fairly uniform, comprise dunal sands and have comparatively high hydraulic conductivity (Bomblies *et al.* 2008). Input files are provided to describe the proportional composition of the surface soil layer and underlying soil layers in terms of sand, clay and silt.

The unsaturated zone model was calibrated as described in Bomblies *et al.* (2008), using field measurements of soil moisture from 2005. Validation was performed using soil moisture measurements from 2006. 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). Values for these four parameters were assigned to each discrete soil layer to parameterize the unsaturated zone water redistribution according to Campbell's model.

Meteorological inputs of precipitation, relative humidity, wind speed, wind direction, air temperature and incoming solar radiation are provided from observations. Precipitation data beginning 1st July 2005 was provided at hourly intervals by Institut de Recherche pour le Développement (IRD) in Niamey, Niger, through the African Monsoon Multidisciplinary

Analyses program. Other meteorological variables were recorded at 15-minute intervals by a meteorological station erected in Banizoumbou in August 2005 (Bomblies *et al.* 2008).

3.3 Scenario Descriptions

This modeling investigation focused on the modification of one pool, shown in Figure 3. The pool is located on the outskirts of Banizoumbou to the southwest of the village, as shown in Figure 4. This pool does not exist during the dry season, but during the rainy season it has been observed at a maximum size of approximately 60 m x 40 m and with a maximum depth of approximately 35 cm. 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. The pool has been observed to contain many sub-adult (larvae and pupae) *Anopheles gambiae s.l.* mosquitoes and is thought to contribute significantly to the mosquito populations that become abundant in Banizoumbou during the rainy season.

Figure 3: Pool located to southwest of Banizoumbou, used in model simulations as the focus for environmental management interventions. Photograph taken 20th August 2007.

The investigation simulated habitat modifications in the form of leveling the topographic depression where the pool typically forms, ploughing the surface soils of the pool to enhance infiltration, and erecting barriers to hillslope runoff to reduce the size of the pool. For each type of modification, the scenarios were run using 2005, 2006 and 2007 precipitation and meteorological observations to determine how these techniques performed under different climatic conditions.

In each year, the first rains arrived in late May or early June and rainfall was consistent throughout July and August. Rainfall decreased during September and the dry season began in October. Precipitation and meteorological data collection began in late June in 2005 so the simulation period for that year began 1st July and ended 31st October. Data collection was continuous from July 2005 until September 2007, so the simulation period in 2006 was 1st June to 31st October. The simulation period in 2007 also began 1st June. In mid-September 2007, the field equipment began experiencing problems with the battery supply and data was sporadically collected after 16th September 2007. Therefore the simulation period in 2007 was truncated at 16th September, despite the presence of pools and rainfall at this time, in order to avoid using spurious data.

Model output from each simulation consisted of a time series of water depth in the centre of the pool over the length of the simulation period and raster grids of water depth across the domain for each time step in the simulation period. The output was analyzed to determine the effect of the different management techniques on maximum pool depth, pool extent and persistence time.

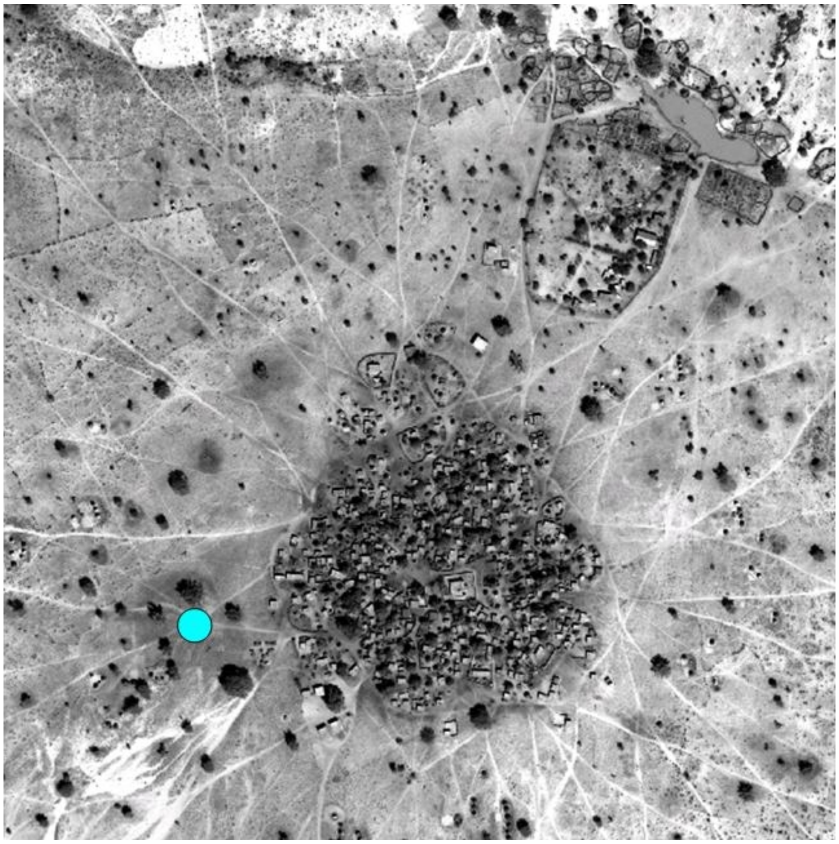

Figure 4: Location of pool altered in modeling investigation. The blue circle shows the approximate location of the pool altered in the modeling simulations.

Leveling the topographic depression

Leveling of the topographic depression involved raising the base of the depression and lowering the elevation of the surrounding land, such that the depression became much shallower and spread over a greater area. The volume of sand is conserved in this process, just redistributed to achieve a shallower depression. The objective of this method was not to prevent runoff from settling in the depression, but rather to spread the runoff over a greater area with a shallower depth. By doing so, evaporation and infiltration processes would be enhanced and therefore the pool should dissipate more quickly than it would under natural conditions. This technique therefore sought to reduce the persistence time of the pool. 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. By leveling the pool and decreasing its 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.

Leveling of the depression is a technologically simple technique, requiring only labor resources and the time required to carry out the work. Once a depression is leveled, it would require periodic maintenance work to ensure that erosion or compaction processes have not altered the effect of the leveling. Therefore it is considered that if leveling can be shown as an effective method to manage breeding pools, it could be a very sustainable way to contribute to malaria control.

To simulate leveling of the pool depression, the digital elevation model (DEM) was modified over an area of approximately 1.5 ha. This area includes the main pool area and some of the surrounding land, which is cultivated for millet production during the rainy season. The DEM was modified using the geographical information system (GIS) program ArcGIS. The original DEM raster file was converted to a point shapefile and then individual points in the vicinity of the pool were edited to change the topography in that localized area. The point shapefile was then converted back into a raster file and exported as an ascii grid for use in the model.

The existing topography in the vicinity of the target pool has a minimum elevation of 209.3 m (relative to mean sea level) in the centre of the pool. Model simulations were undertaken using four different DEMs: the original existing topography (DEM 1), leveling to make the minimum elevation 209.45 m in the centre of the pool (DEM 2), leveling to make the minimum elevation 209.65 m in the centre of the pool (DEM 3) and leveling to make the minimum elevation 209.75 m in the centre of the pool (DEM 4). Figure 5 below shows the new topography in the vicinity of the pool for each simulation. The dotted cross marks the centre of the location where the pool currently forms.

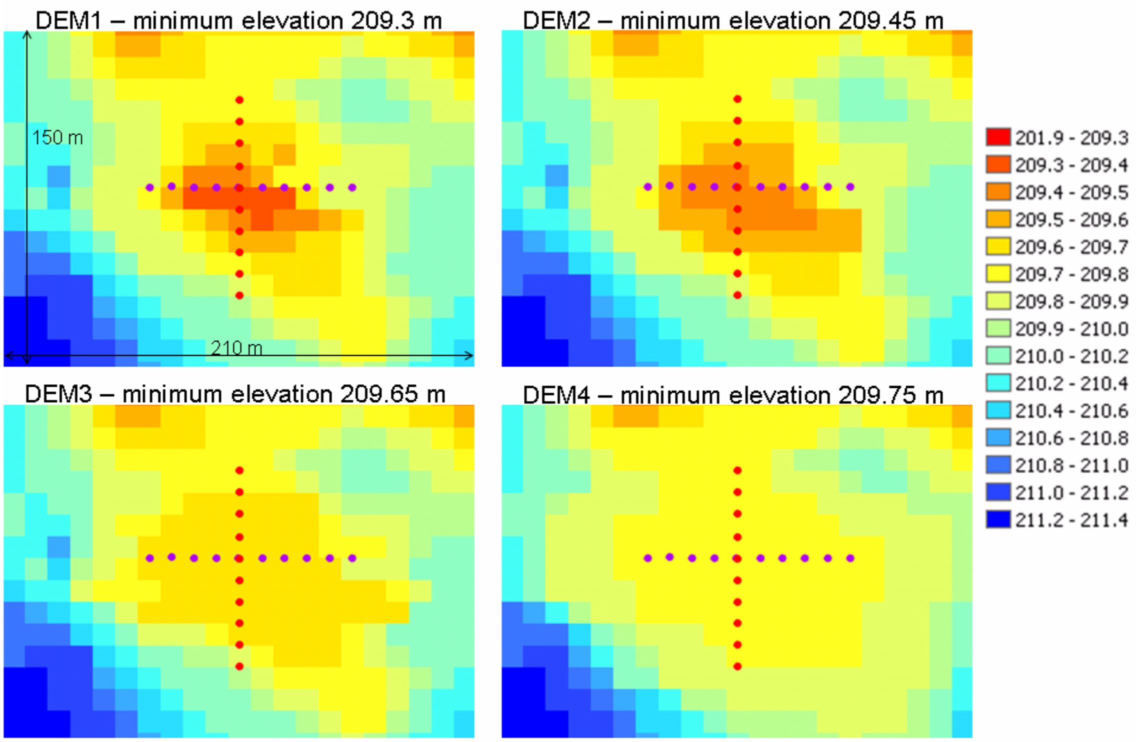

Figure 5: Digital elevation models used for simulating leveling of the topographic depression. The legend shows the elevation in metres (relative to mean sea level) of each grid cell. The dotted cross marks the centre of the existing pool.

The change in elevation in this area can also be shown through hypsometric curves, as in Figure 6 below. The hypsometric curves show, for each DEM, the relative change in elevation with area, normalized to the maximum and minimum elevations in each DEM. The curves show the progression through the leveling process, from an initial topography that is continuously sloping from the outsides to the centre of the pool area, to a topography that slopes only on the outside, with a large flat base area. This progression in topographic change as shown by hypsometric curves is analogous to the theory of basin aging through erosion processes.

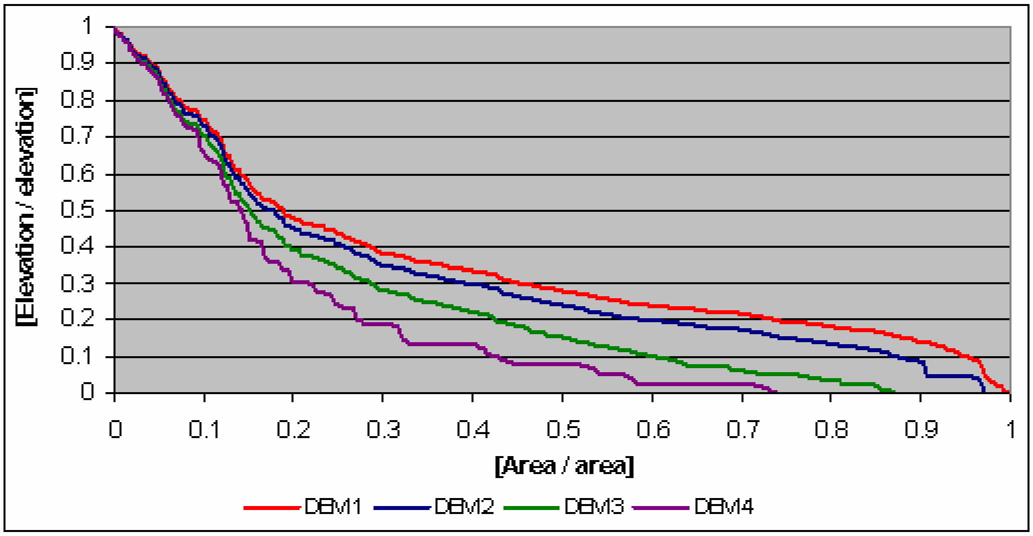

Figure 6: Hypsometric curves for leveling of pool depression scenarios.

Ploughing surface soils

Ploughing of the surface soils involved increasing the hydraulic conductivity assigned in the model to the surface soil within the base of the depression where the pool forms, to simulate the break up and removal of the surface crust layer. This technique aimed to increase the infiltrability of the area where runoff collected in order to decrease the time for which the pool persists. As described above, the objective was to force the pool to persist for less time than would be required for establishment of breeding pool habitat. This technique would also be easy to implement by residents and could be achieved by turning over the surface of the pool basin with the tools used for weeding in millet fields, in the same way that the soil crust is broken up in fields to allow rain to penetrate to the crop roots.

Each grid cell within the model domain is assigned soil characteristics via the soil input files. These files designate each grid cell to contain a certain proportion of sand, clay and silt, with values assigned for the top soil layer separately to the other soil layers underneath (the underlying soil layers are assumed to be uniform in composition). Certain ratios of sand to clay are assigned different hydraulic conductivity values through a soil parameters input file, with higher proportions of clay being assigned lower hydraulic conductivities. Therefore there are two ways to change the surface infiltrability of grid cells within the model – assign the cell a higher proportion of sand, which will lead the model to assign that cell to a different hydraulic conductivity, or change the soil parameters so that the existing ratio of sand and clay has a higher conductivity. The first method is more time consuming as it requires changing grid cells individually using a GIS program; however it is more selective and allows the remainder of the domain to be unchanged.

To simulate ploughing of the surface soils, the soil input files were changed to increase the proportion of sand relative to clay assigned to the grid cells only within the pool basin, an area of approximately 60 m x 40 m. The pool basin was assigned a higher value of sand compared to the surrounding land area, such that runoff that entered the pool basin would be able to infiltrate quickly. The majority of the surface soils in the domain are assigned 55% sand and 35% clay (the remaining 10% is assumed by the model to be silt). All pools except the target pool for these simulations are assigned 30% sand and 50% clay. The higher clay content in the pools means they are given a lower hydraulic conductivity than the surrounding areas. The target pool for this simulation was assigned 65% sand and 25% clay to give it a higher conductivity than the surrounding soils and to bring the conductivity and soil characteristics closer to the underlying sandy soil layers. The soil input files were modified using ArcGIS. The original sand and clay proportion raster files were converted to point shapefiles and then individual points in the pool basin were edited to change the values of sand and clay. The point shapefiles were then converted back into raster files and exported as ascii grids for use in the model.

Barriers to hillslope runoff

Simulating barriers to hillslope runoff involved raising the level of the land in an approximate barrier shape in the catchment area of the pool to the southwest, where large overland flows can be observed during rain events to scour out sandy channels that feed into the target pool. The objective of this method was to decrease the volume of runoff that settles in the depression, thereby reducing the size and depth of the pool and decreasing its persistence time. It is thought that such a barrier could be built by shoveling sand from the surrounding hillslopes and placing it across the line where major drainage flows occur. The sand would need to be compacted down as much as possible using available tools and, if possible, covered with a thick layer of lateritic gravel to try and minimize the amount of erosion that would occur over the rainy season.

This technique would require considerably more time and labor than the other two above-described techniques. The construction of a barrier that is of sufficient size to block the large runoff flows that occur during rain events would require a team of men and take several days. It would need to be built prior to the rainy season but would most likely require considerable maintenance throughout the season, as runoff and direct rainfall would erode some of the sands and potentially compromise the integrity of the barrier.

To simulate hillslope barriers, the DEM was modified using ArcGIS. The original DEM raster file was converted to a point shapefile and then individual points were edited to change the topography in the shape of two barriers. The point shapefile was then converted back into a raster file and exported as an ascii grid for use in the model.

The barriers created are shown in Figure 7 below. Two barriers were created: one to the west-southwest of the pool and one to the south-southwest of the pool. The barrier to the west-southwest of the pool was approximately 150 m long, running in a northwest-to-southeast direction, approximately 40 m wide, approximately 3 m high and was located approximately 530 m away from the pool. The height of this barrier was 217 m (relative to mean sea level), compared with the adjacent land that is at an approximate elevation of 213-215 m. It was placed directly across a drainage line that is visible on the aerial photograph shown in Figure 4. The barrier to the south-southwest of the pool was approximately 350 m long, running in a northwest-to-southeast direction, approximately 50 m wide, approximately 3 m high and was also located approximately 530 m away from the pool. The height of this barrier was 225 m (relative to mean sea level), compared with the adjacent land that is at an approximate elevation of 221-223 m. This second barrier was larger because it was placed directly across a large drainage channel that is visible on Figure 4 as an area of white sand, where large runoff flows in previous years have led to significant scouring of the hillslope. Figure 7 shows the direction of hillslopes in the area and the relative changes in topography made to the DEM to simulate these barriers.

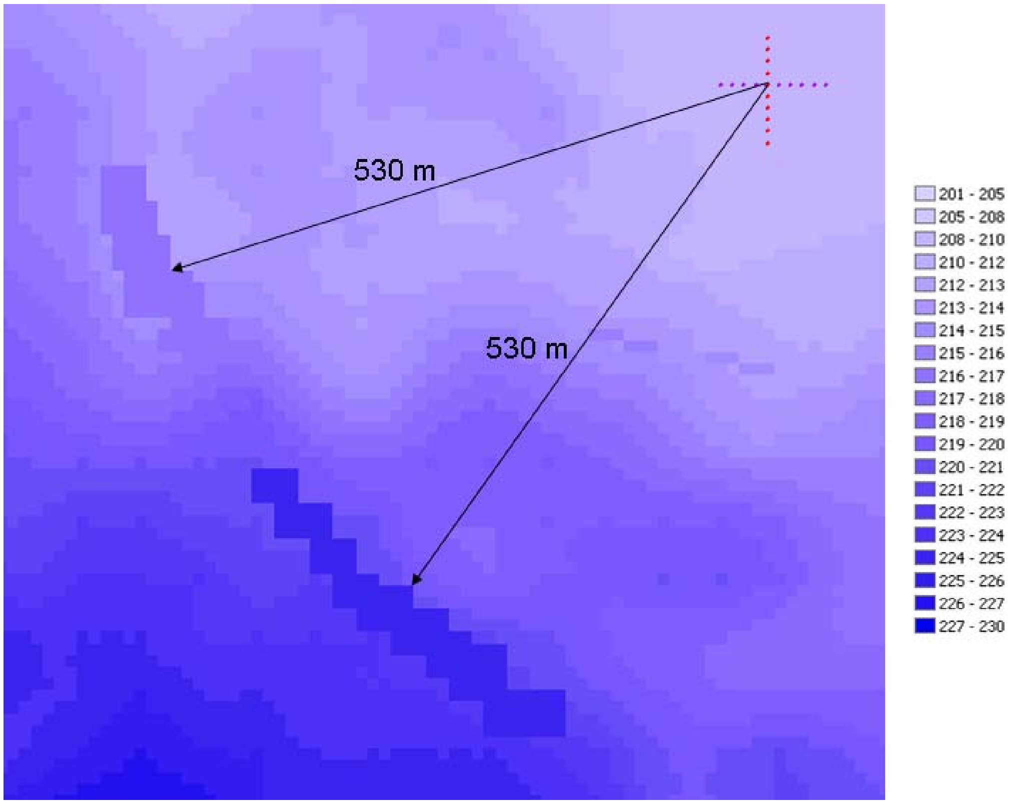

Figure 7: Topography changes made to simulate barriers to hillslope runoff. The legend shows the elevation in metres (relative to mean sea level) of each grid cell. The dotted cross marks the centre of the existing pool.

3.4 Results

Output from each model simulation included the water depth at the center of the southwest pool as a function of time and a spatial grid of water depth at each point across the domain, output every hour of the simulation. The time series of water depth in the center of the pool was used to determine the persistence time of the pool each time it formed during each rainy season. The persistence time is important for considering how long the pool might be available as a breeding habitat for *Anopheles* mosquitoes. The water depth grids generated across the domain were used to calculate the areal extent of the pool at times corresponding to maximum pool depths, which was used to calculate an approximate volume of water contained within the pool and also indicated how much surface area would be available as breeding habitat.

3.4.1 Model Performance

The model simulation of the southwest pool formation using existing topography (DEM1) in each year was compared with observations of the pool's formation to determine if the model representation of pool dynamics was sufficiently accurate for this study. Although quantitative measurements of pool size and depth have not been previously recorded, observations of pool presence or absence were made on approximately a weekly basis throughout the 2005, 2006 and 2007 rainy seasons. These observations were compared to the model output to assess the ability of the model to capture the pool's formation dynamics, as shown in Table 1.

There were a total of 22 observations made of the southwest pool in 2005, 15 observations in 2006 and 28 observations in 2007. Table 1 shows that during these observations, the pool was present on 11 occasions in 2005, 12 occasions in 2006 and 20 occasions in 2007 and was absent on the remaining occasions. Model output of water depth in the southwest pool on the days when observations were made in each year was compared to determine if the model correctly predicted the presence or absence of the pool.

Table 1 shows that the model predicted the pool to be present on every day that an observation was made during each simulation period. The model therefore correctly predicted the presence of the pool on 100% of the occasions when the pool was actually observed to exist but it failed to predict the absence of the pool on any occasion when the pool was observed not to exist. Although the model shows a dynamic nature of the pool, with collected water gradually dissipating due to infiltration and evaporation processes, it generally over-predicts the presence of the pool, such that in the model the pool persists for longer time periods than it was observed to persist.

Table 1: Comparison of pool presence observations with model output for each simulation year

	2005	2006	2007
No. occasions observed presence	11	12	20
No. occasions observed absence	11	3	8
No. occasions modeled presence	22	15	28
No. occasions modeled absence	0	0	0
Model performance – presence	100%	100%	100%
Model performance – absence	0%	0%	0%
Summary performance	50%	80%	71%

One possible explanation for this over-prediction of pool presence is the dynamic nature of the soil characteristics in the region surrounding Banizoumbou. A value of 0.1 for surface roughness (as given by Manning's *n* coefficient) has been applied uniformly across the model domain. This value has been set fairly low to account for the surface soil crusting that is observed in the region over most of the year and which produces high rates of runoff. However, during the months of June to October when the millet fields are being actively ploughed and tended to, the processes of ploughing and weeding remove the surface soil crust layer and make the soil more permeable. The presence of growing crops and native vegetation that responds to the onset of the rainy season also acts to slow down hillslope runoff and increase infiltration at source. Therefore, it is likely that the surface roughness would effectively increase over the length of the simulation period to reflect the growing vegetation and field cultivation. This would cause slower runoff rates and allow for greater infiltration on the hillslope areas that contribute to the southwest pool. In turn, this would act to decrease the amount of runoff into the pool, reducing its persistence time or preventing it from forming altogether. Setting the soil infiltration rate too high in the model could account for the observations of no pool presence during times when the model has simulated pool formation.

Although the model generally over-predicts the presence of the pool, it does reasonably well at simulating the dynamic nature of the pool formation. Also, the objective of this investigation is to determine whether various intervention techniques are able to reduce the persistence time and extent of the pool compared to the existing situation. Thus the important outcome is the difference between the pool's characteristics before and after the technique has been applied and not the absolute value of the modeled output. It is therefore considered that the model performance is sufficient for carrying out this investigation into the effects of intervention techniques on pool dynamics.

3.4.2 Effect on Water Depth

The water depth at the centre of the pool for each of the four DEMs is shown as a time series in Figure 8 (for 2005), Figure 9 (for 2006) and Figure 10 (for 2007). Water depth in each figure is measured along the left-hand axis and precipitation against the right-hand axis. The figures show that for each rainfall event throughout the simulation period, the maximum water depth reached in the centre of the pool decreases with decreasing depth of the pool depression (i.e. increased leveling). 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 less than 15 cm. The water dissipates at the same rate regardless of the DEM used or water depth in the pool, but increasing degrees of leveling lead to the pool disappearing more quickly due to a lower depth of water. There is a particularly marked decrease in water depth between DEM 2 and DEM 3, suggesting that this range of water depth represents a critical range for pool persistence.

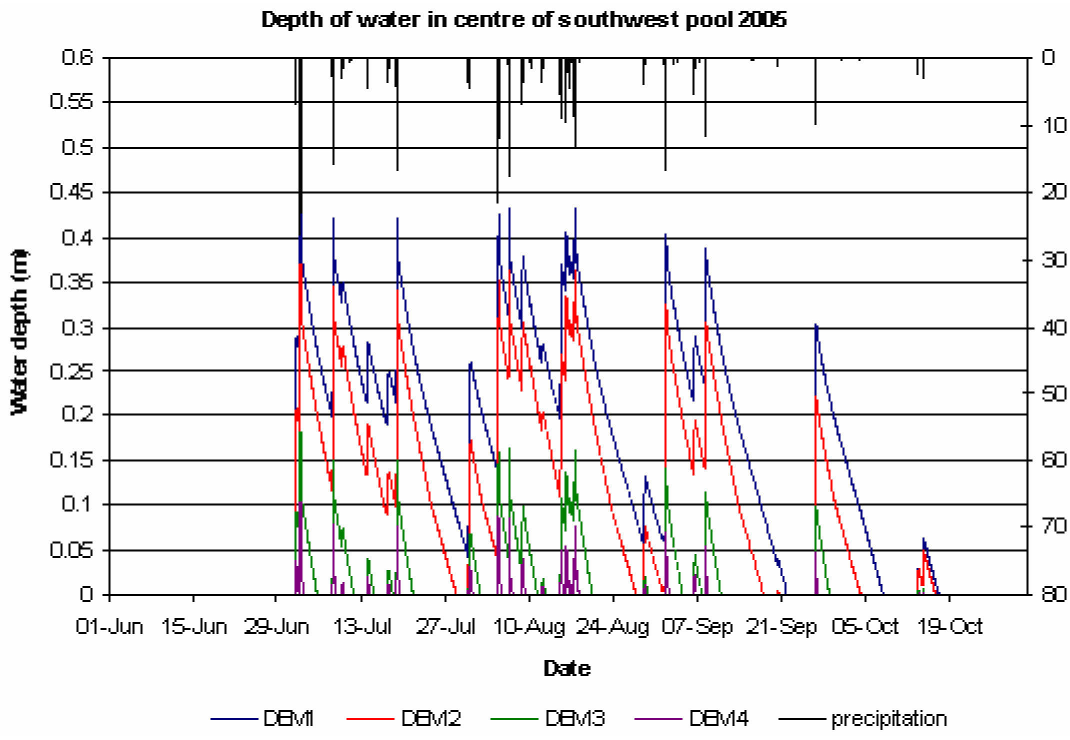

Figure 8: Time series of water depth at the pool centre for each of the four DEMs in 2005

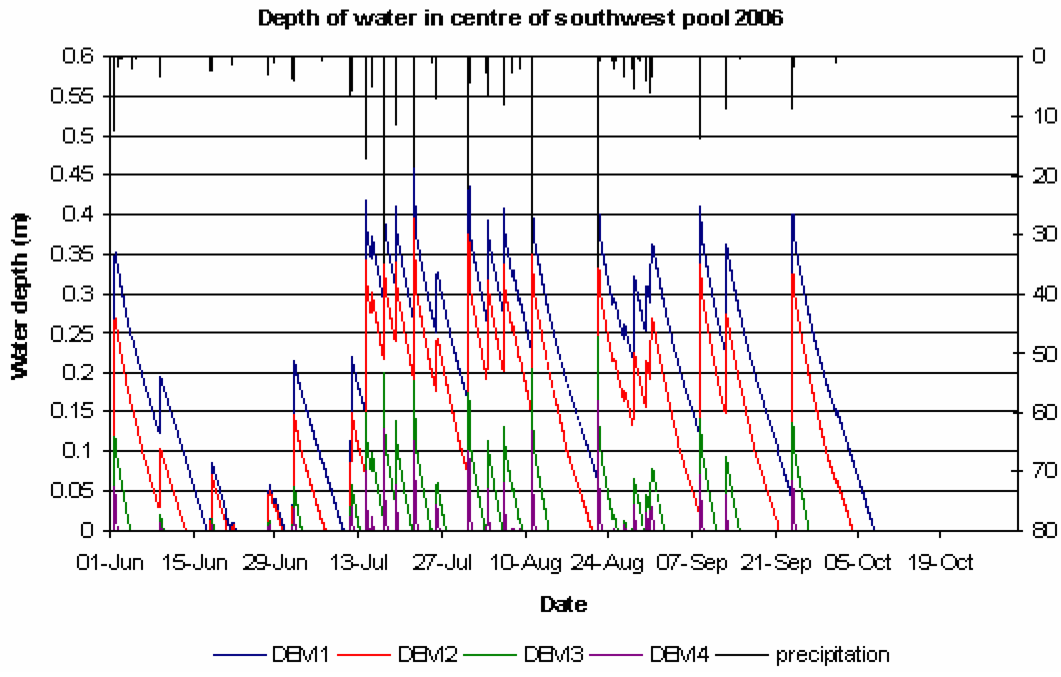

Figure 9: Time series of water depth at the pool centre for each of the four DEMs in 2006

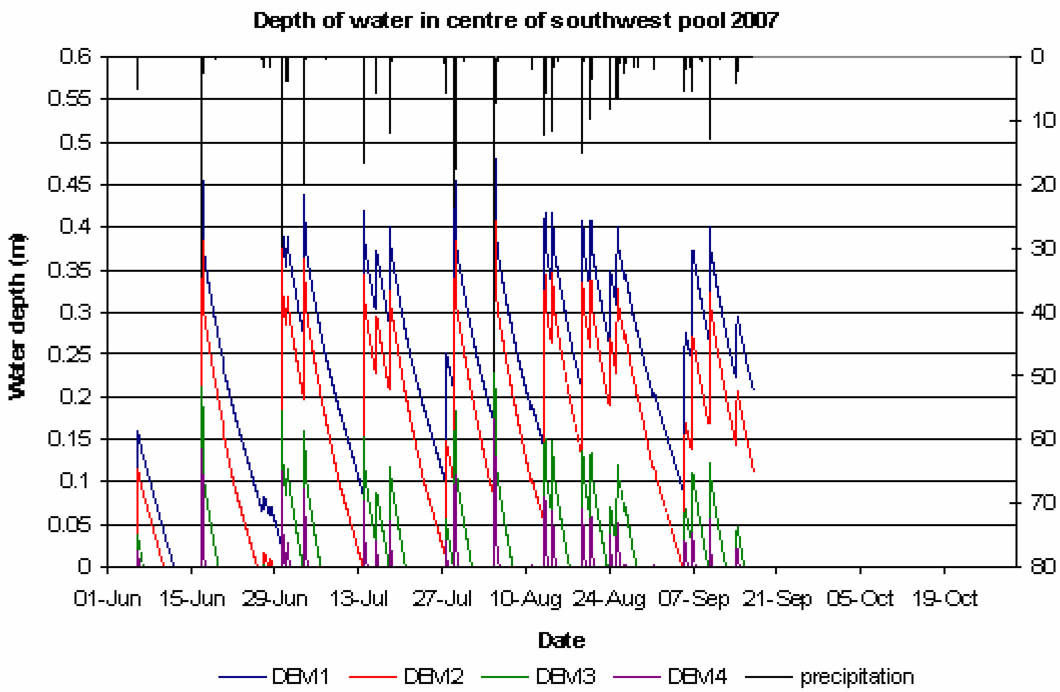

Figure 10: Time series of water depth at the pool centre for each of the four DEMs in 2007

The water depth at the centre of the pool is shown as a time series for the scenarios involving ploughing of the surface (increased permeability) and hillslope runoff barriers in Figure 11 (for 2005), Figure 12 (for 2006) and Figure 13 (for 2007). Water depth in each figure is measured against the left-hand axis and precipitation against the right-hand axis. The existing topography is shown by the line ‘DEM 1’ and existing topography with surface ploughing is shown by ‘DEM 1 high inf’ (for high rates of infiltration). Construction of hillslope runoff barriers with no change to the pool basin topography is shown by ‘DEM 1 runoff barrier’.

The figures show that both the techniques decrease the persistence time of the pool compared with the existing situation. Ploughing of the surface changed the permeability of the surface soil layer, which increased the infiltration rate within the pool basin and led to more rapid dissipation of the pool. The existing modeled dissipation rate (scenario DEM 1) was approximately 1.7 mm/hr, compared with approximately 3.5 mm/hr with surface ploughing. The dissipation rate of the pool is not constant over the pool area or between rainfall events since the pool basin may spread over grid cells defined in the model with different permeabilities (different ratios of sand to clay). The hillslope runoff barrier significantly reduced the amount of water entering the pool basin, decreasing the maximum water depth attained in the pool from about 45 cm to about 10 cm.

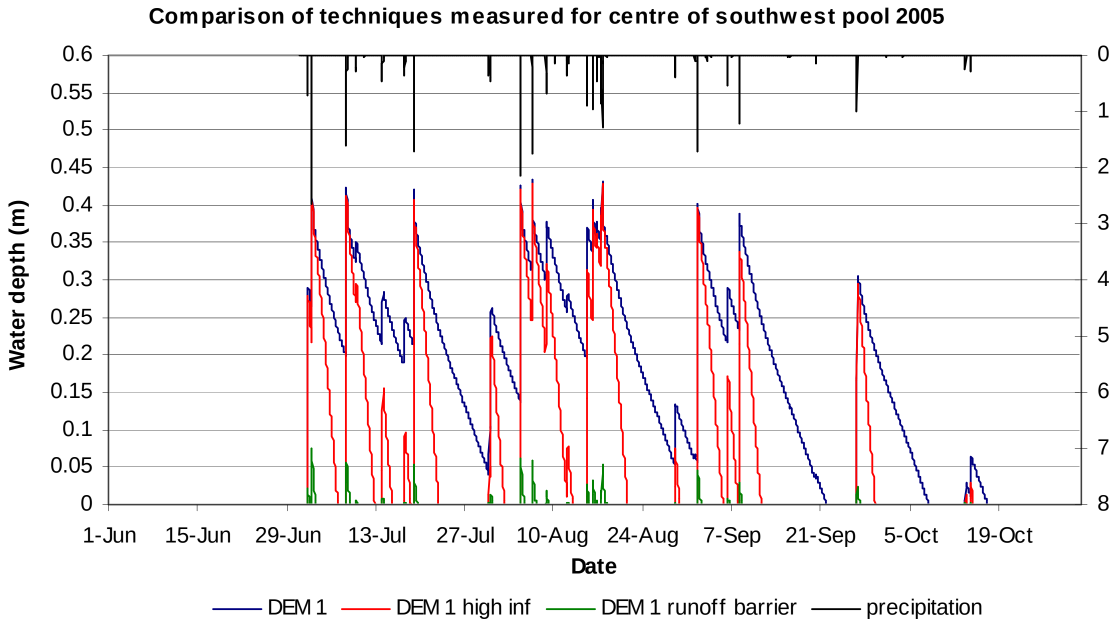

Figure 11: Time series of water depth at the pool centre for the surface ploughing and hillslope runoff barrier scenarios in 2005. The existing situation is shown by DEM 1, the existing topography with surface ploughing by 'DEM 1 high inf' and the hillslope runoff barrier by 'DEM 1 runoff barrier'.

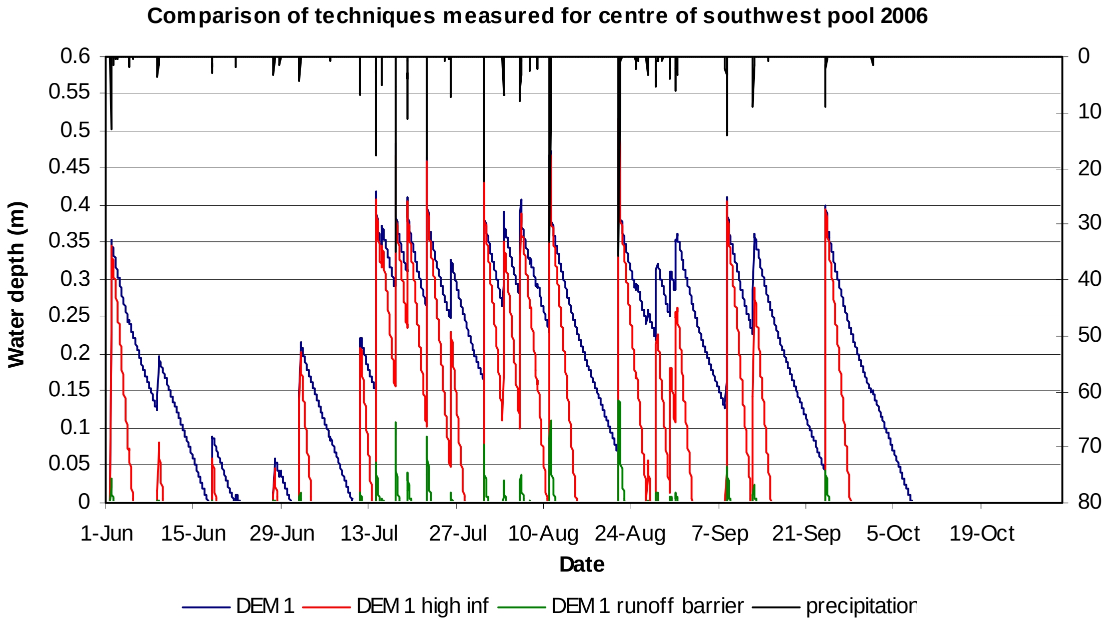

Figure 12: Time series of water depth at the pool centre for the surface ploughing and hillslope runoff barrier scenarios in 2006.

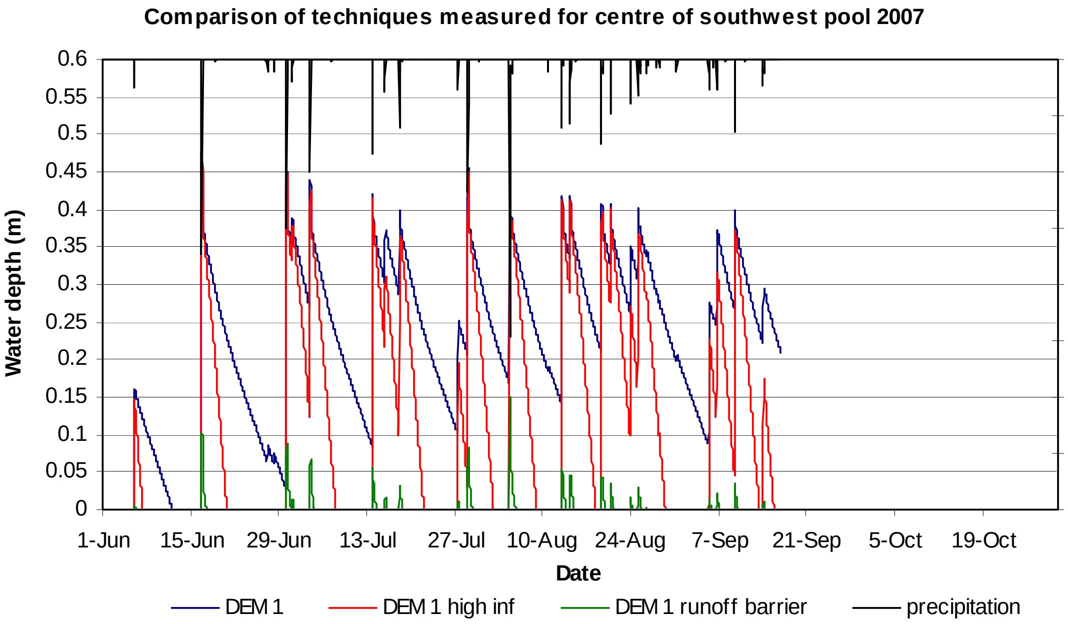

Figure 13: Time series of water depth at the pool centre for the surface ploughing and hillslope runoff barrier scenarios in 2007.

3.4.3 Effect on Areal Extent

The effect of each of the intervention scenarios on the areal extent of the pool can be seen in the figures below. The impact of leveling the pool and decreasing its maximum depth was to spread the pool out over a much larger area, as illustrated in Figure 14. The figure shows the areal extent of the pool over each of the four DEMs during a rain event that occurred 24th September 2005, and is indicative of the changes to the pool extent in each of the simulation periods. The dotted cross in each of the four panels represents the existing location of the pool. The deeper topography of DEM 1 has the smallest areal extent and as the topography becomes shallower, the area of the pool increases to a maximum with DEM 4.

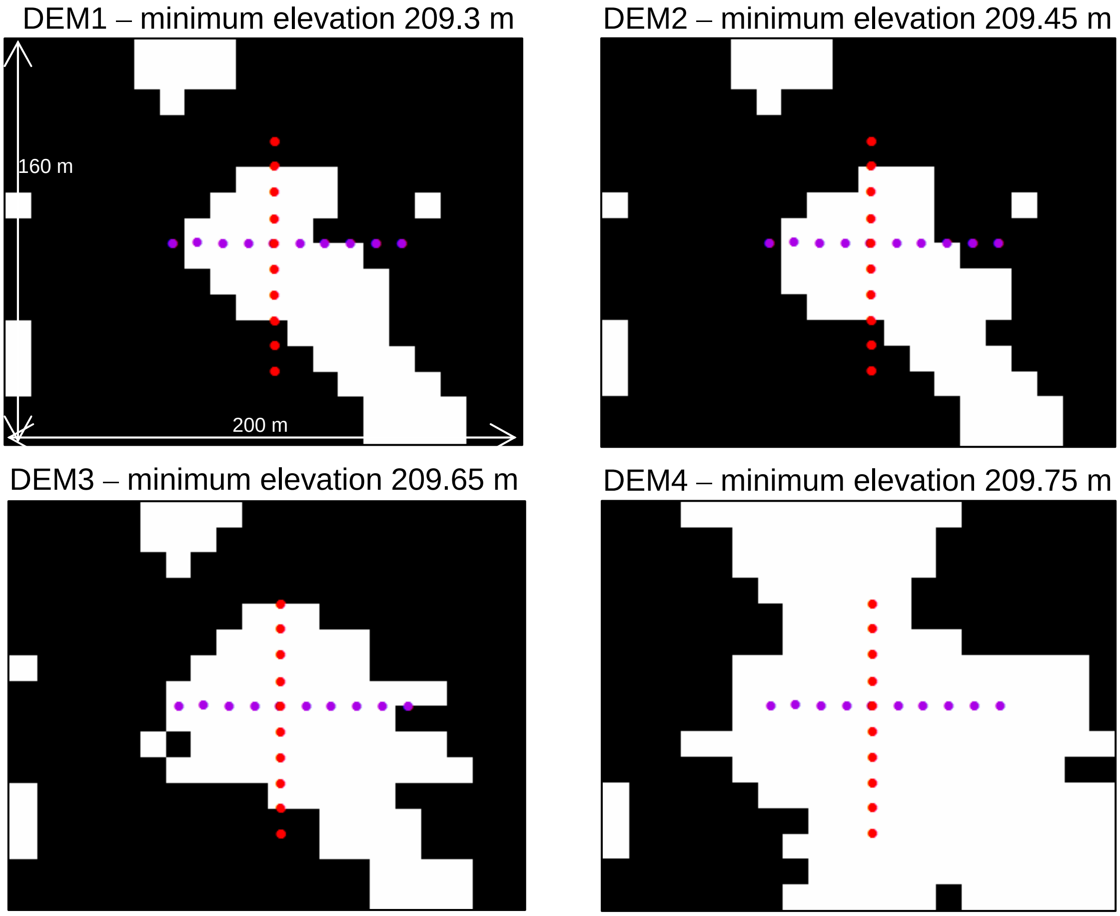

Figure 14: Areal extent of the pool during a pooling event for each of the four DEMs in 2005. In each panel, black represents a dry grid cell and white represents a wet grid cell.

The relationship between areal extent and depth of the pool for each of the four DEMs is shown in Figure 15, Figure 16 and Figure 17 below. The figures show the maximum areal extent and maximum water depth attained within the pool for each discrete pooling event in 2005, 2006 and 2007 respectively. A pooling event was defined as the length of time that the model output predicted water to exist in the centre of the pool continuously. If the model recorded no water in the centre of the pool, i.e. it dried out completely, then the next time that water was recorded in the pool became a new pooling event. The figures show that as the topography becomes shallower with increasing degrees of leveling, the areal extent of the pool for a given depth becomes larger.

It must be noted that in 2006 and 2007, the pools formed with DEM4 occasionally became so large that they overflowed the basin where the southwest pool normally forms and flowed northward, joining up with another small pool that forms about 50 m from the southwest pool. This is not considered an optimal outcome, as extended flooding could transfer problems away from the original pool basin and create other problems downstream. It is therefore desirous to keep the pool volume confined within the original basin. To this end, DEM3 is considered to represent the optimal balance between reducing the water depth of the pool and minimizing the extent of flooding.

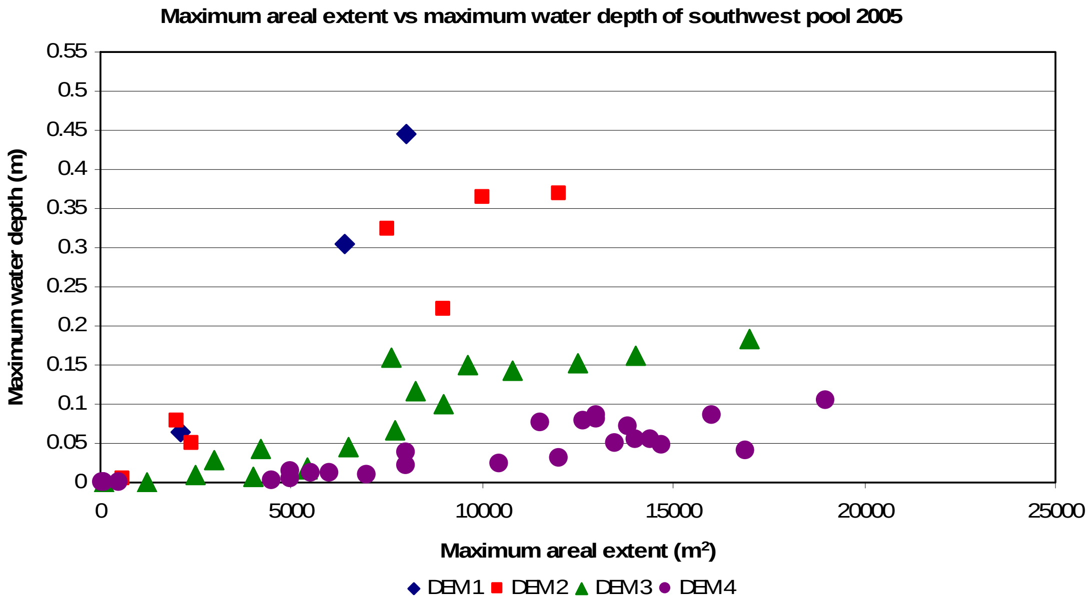

Figure 15: Maximum areal extent and maximum pool depth for each of the four DEMs in 2005

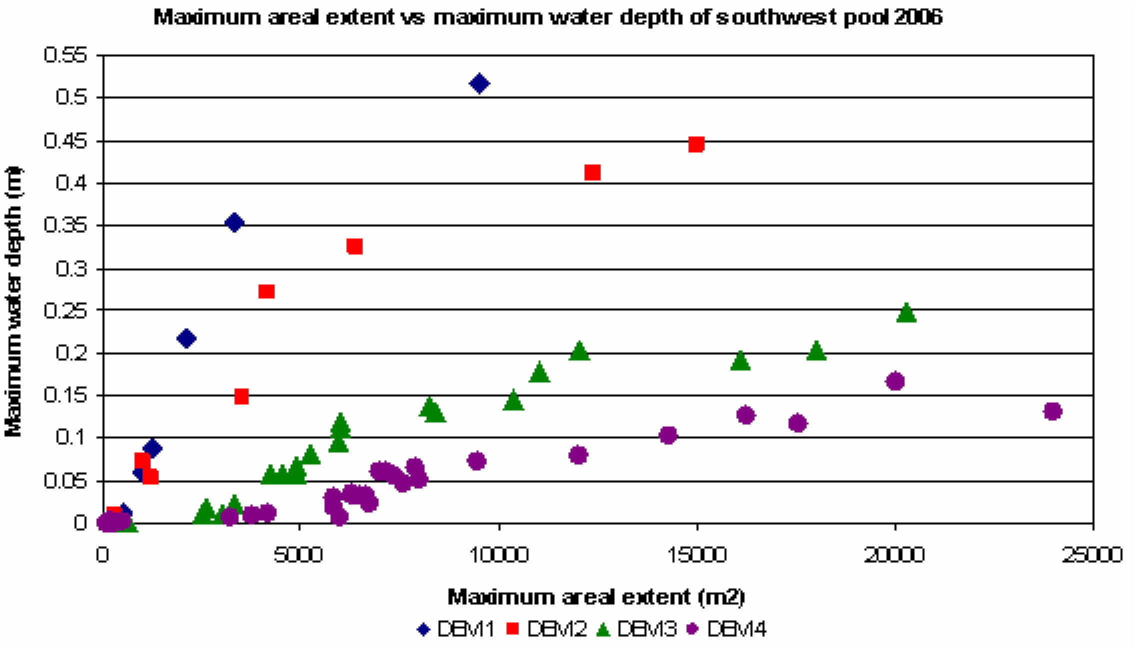

Figure 16: Maximum areal extent and maximum pool depth for each of the four DEMs in 2006

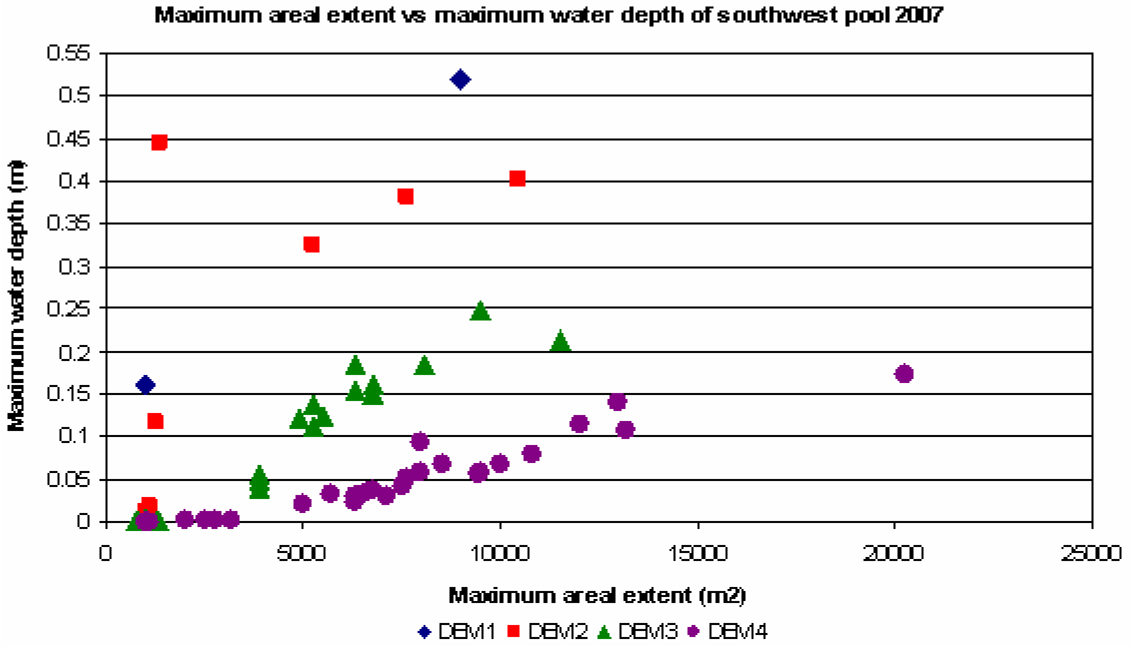

Figure 17: Maximum areal extent and maximum pool depth for each of the four DEMs in 2007

The relationship between areal extent and depth of the pool for the scenarios involving ploughing of the surface (increased infiltration rate) and hillslope runoff barriers is shown in Figure 18, Figure 19 and Figure 20 below. The figures show the maximum areal extent and maximum water depth attained within the pool for each discrete pooling event in 2005, 2006 and 2007 respectively. The existing topography is shown by ‘DEM 1’ and existing topography with surface ploughing is shown by 'DEM 1 high inf' (for high rates of infiltration). Leveled topography is shown by 'DEM 3' and surface ploughing combined with leveling by 'DEM 3 high inf'. Construction of hillslope runoff barriers with no change to the pool basin topography is shown by 'DEM 1 runoff barrier'.

The figures show that the leveling and hillslope runoff barrier techniques have a significant impact on the water depth to areal extent relationship, creating pools that cover a much larger area than the existing topography for the same water depth. However, the surface ploughing technique has no impact on the areal extent of the pool for a given depth. These results are to be expected since both the leveling and hillslope runoff barrier techniques reduce the water depth that is attained in the pool basin: the leveling technique maintains the pool volume but changes the depth to area ratio and the hillslope runoff barrier reduces the total volume of water that collects in the pool basin. The surface ploughing technique does not affect the size or dimensions of the pool, only the rate at which it dissipates.

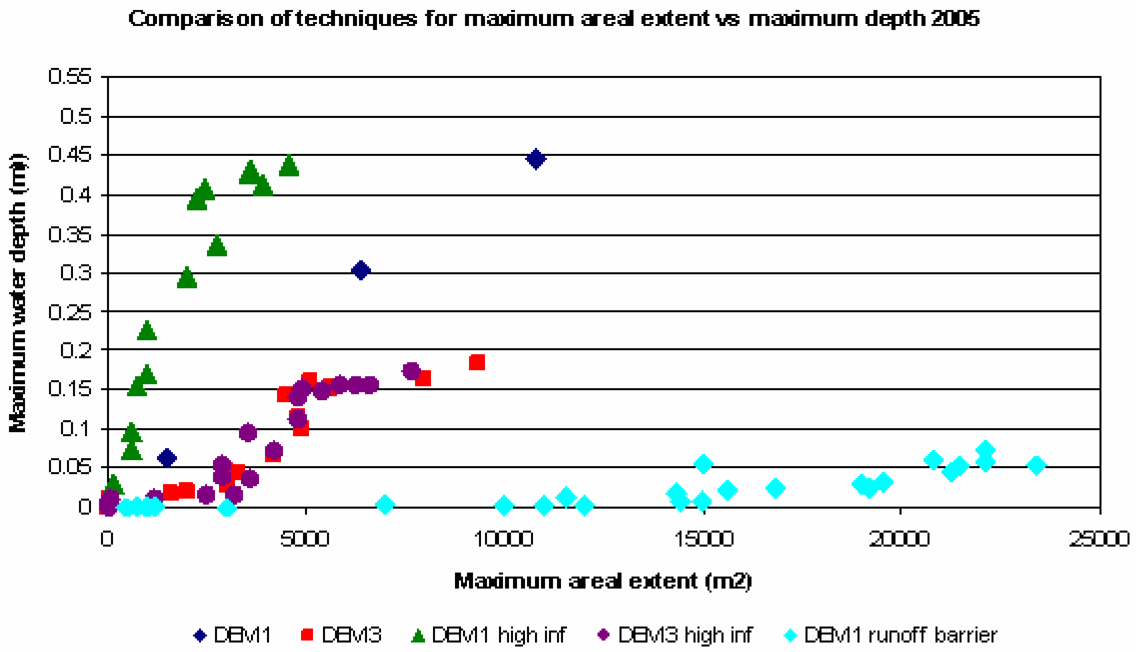

Figure 18: Maximum areal extent and maximum pool depth for the surface ploughing and hillslope runoff barrier scenarios in 2005. The existing situation is shown by DEM 1, the existing topography with surface ploughing by 'DEM 1 high inf', levelled topography by DEM 3, leveling plus surface ploughing by 'DEM 3 high inf' and the hillslope runoff barrier by 'DEM 1 runoff barrier'.

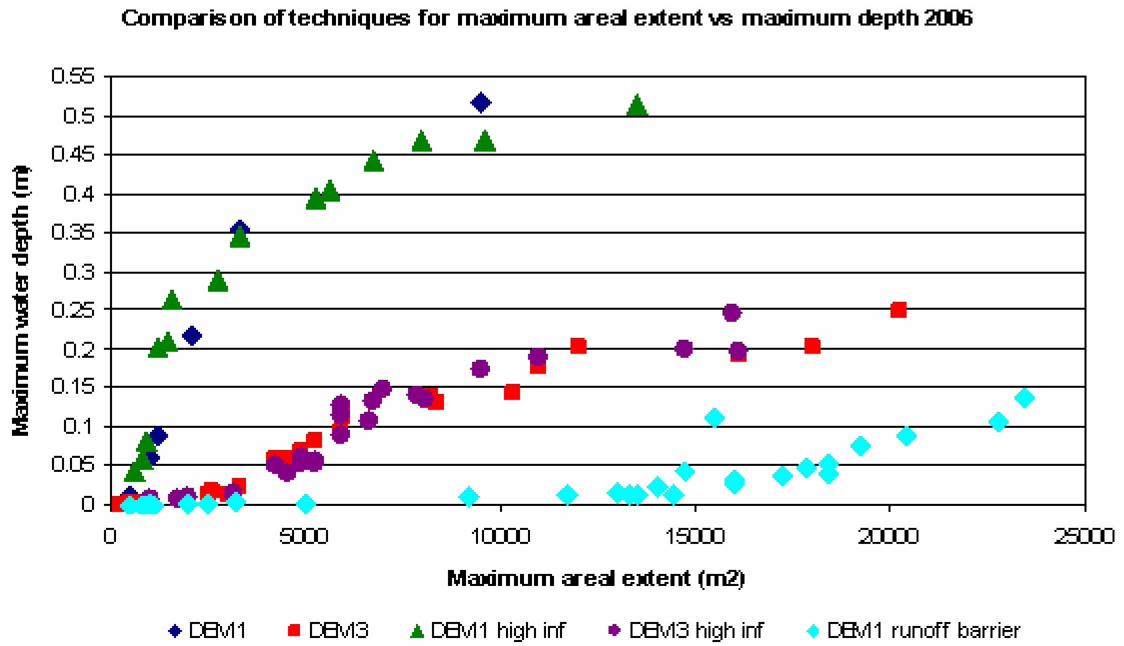

Figure 19: Maximum areal extent and maximum pool depth for the surface ploughing and hillslope runoff barrier scenarios in 2006.

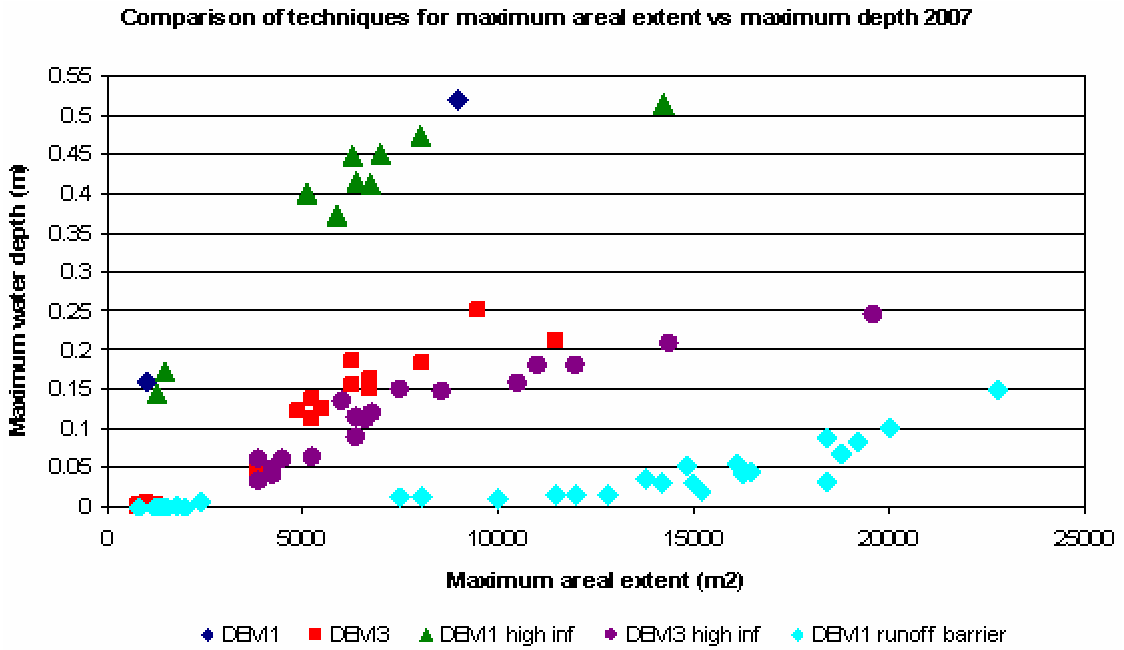

Figure 20: Maximum areal extent and maximum pool depth for the surface ploughing and hillslope runoff barrier scenarios in 2007.

Figures 18, 19 and 20 show that the hillslope runoff barrier technique creates pools that are significantly larger in area than either of the other techniques or the existing topography. An important concern with this kind of technique is that runoff diverted from the problem pool (in this case the southwest pool) may simply be channeled into another location, where it can cause unintended problems such as flooding of domestic residences or creation of new mosquito breeding habitats. Figure 21 illustrates the difference in runoff collection locations between the existing topography (shown in the top panel) and with the hillslope runoff barrier (shown in the bottom panel) during a rain event in 2005. The blue shading in the figure indicates the depth of water that collects after the rain event. The dotted cross indicates the centre of the depression where the southwest pool currently forms.

The figure shows that under the existing topography, water is directed to specific localized depressions in the topography, such as the southwest pool. When the hillslope runoff barrier technique is simulated, runoff is more evenly distributed across the landscape, creating shallower areas of flooding that cover a much greater area. The runoff barrier causes the southwest pool to become extremely large, such that it connects to a smaller pool that previously formed immediately adjacent to it on the north side. This leads to a pool that is approximately twice the size of the original. It is considered that such extensive flooding is not a desirable outcome, and thus this method of intervention would not be recommended for this pool.

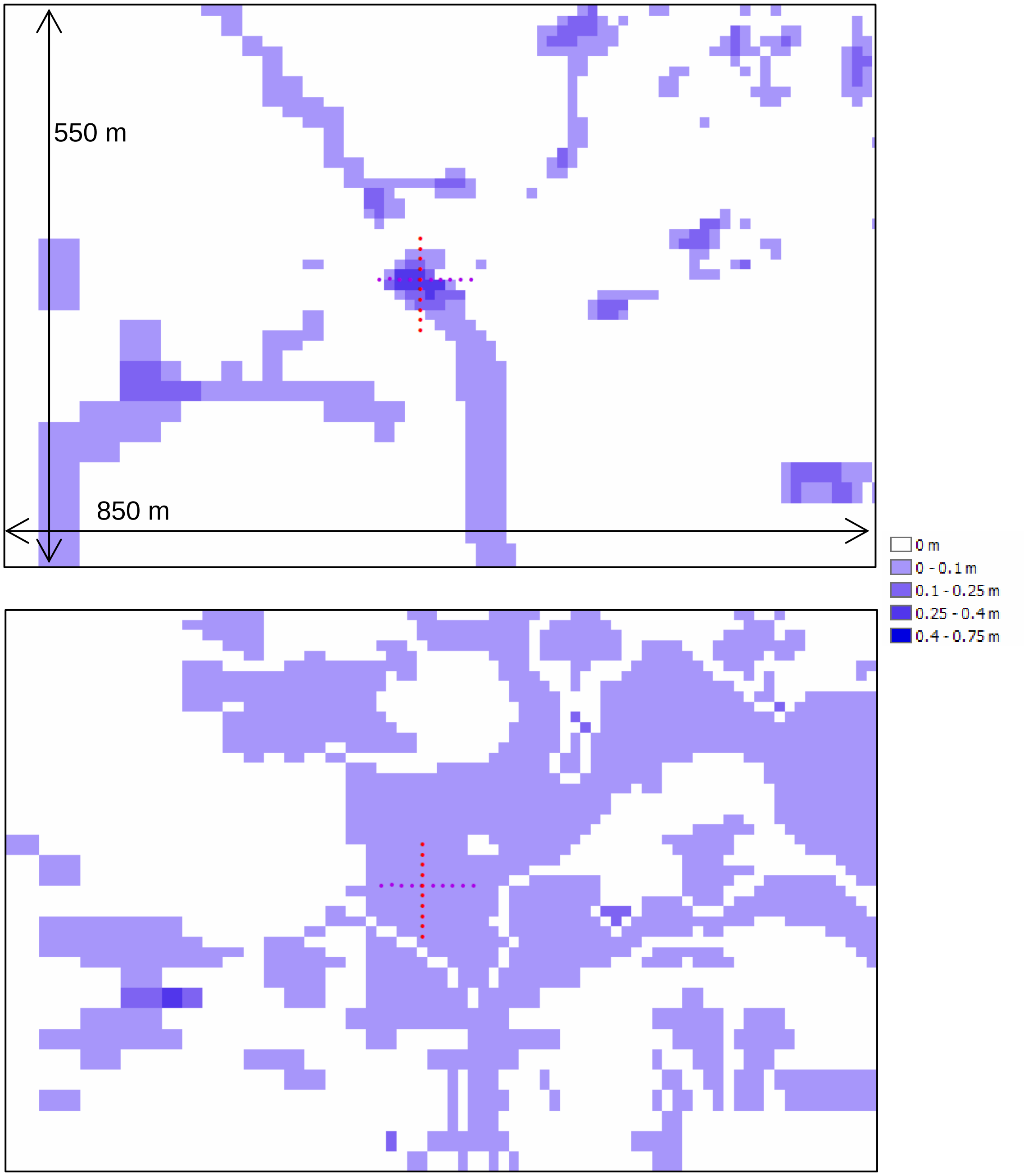

Figure 21: Comparison of water pool locations under existing topography (top) and with the hillslope runoff barrier technique (bottom) for a pooling event in 2005. The location of the southwest pool is shown by the dotted cross. The blue shading indicates the depth of water.

3.4.4 Effect on Persistence Time

The effect of each of the intervention scenarios on the persistence time of the pool can be seen in the figures below. The length of each pooling event was defined as the persistence time of that pool.

Figure 22, Figure 23 and Figure 24 depict the persistence time and maximum water depth attained in the pool during each pooling event in 2005, 2006 and 2007 respectively for each of the four DEMs (i.e. the leveling scenarios). Figure 25, Figure 26 and Figure 27 show the persistence time and maximum areal extent of each pooling event in 2005, 2006 and 2007 for each of the four DEMs. The figures are all shown on a log-linear scale.

The results show that there is a non-linear relationship between persistence time of a pool and maximum water depth attained in the pool in each year. With the existing topography, the pool persists for a long time in each year, only drying out completely on three occasions in 2005, six occasions in 2006 and two occasions in 2007 during the simulation period. Water is able to accumulate to a high level during these long persistence times, leading to the high maximum water depths shown in the figures. As the topography becomes shallower with DEM 2, DEM 3 and DEM 4, the pool persists for shorter periods of time and does not reach the same maximum water depths, drying out completely many more times throughout the simulation period (as indicated by the large number of discrete pooling events). Figures 15, 16 and 17 illustrated that the shallower water depths attained under the leveling scenarios were due to increases in areal extent of the pool. Figures 25, 26 and 27 show that persistence time decreases with increasing areal extent, which allows infiltration and evaporation processes to dissipate the pool more quickly.

The results show that with DEM 3, the pool does not persist for longer than 8 days at a time before drying out completely in any of the simulation years. With DEM 4, the pool does not persist for longer than 1 day. It is important to ensure that a pool’s persistence time is very short in order to remove it as a potential breeding habitat. It is considered that the minimum length of time a pool must persist to become established as a mosquito breeding habitat is about 7 days. Therefore DEM 3 represents a critical topographic level at which the modeled maximum persistence time is approximately equal to the theoretical time for breeding habitat establishment. It was noted above that DEM4 can lead to an areal extent that is not desirous as water begins to flood outside of the original pool basin. Thus although DEM4 appears the best option, in terms of minimizing persistence time, the resultant flooding extent needs to be considered also.

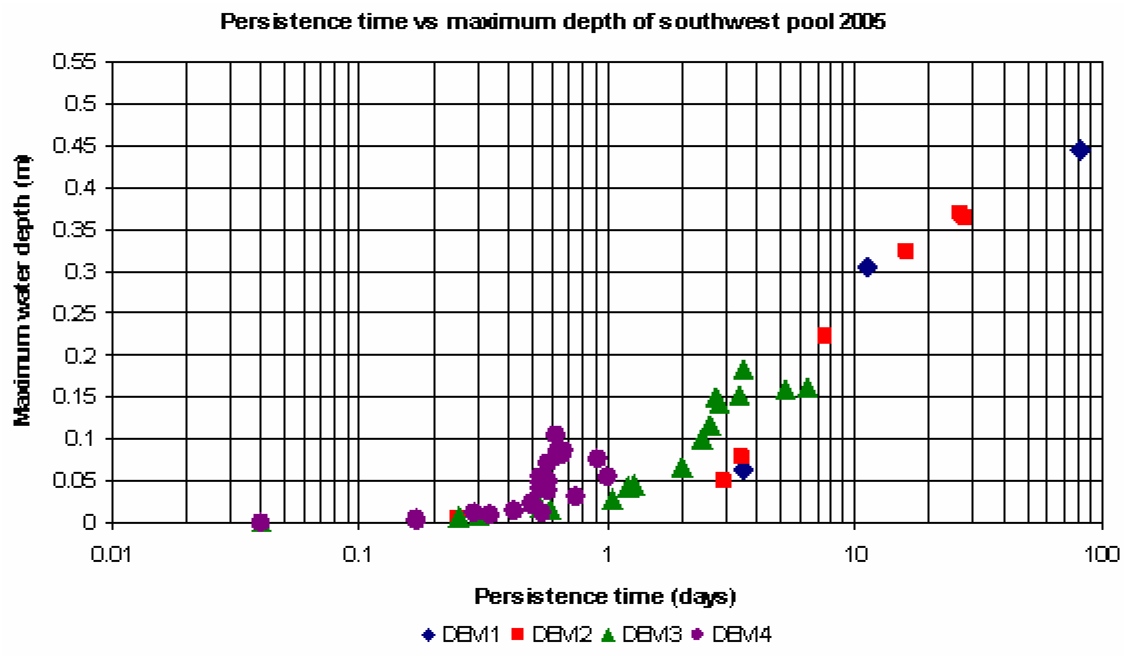

Figure 22: Persistence time and maximum pool water depth for each of the four DEMs in 2005

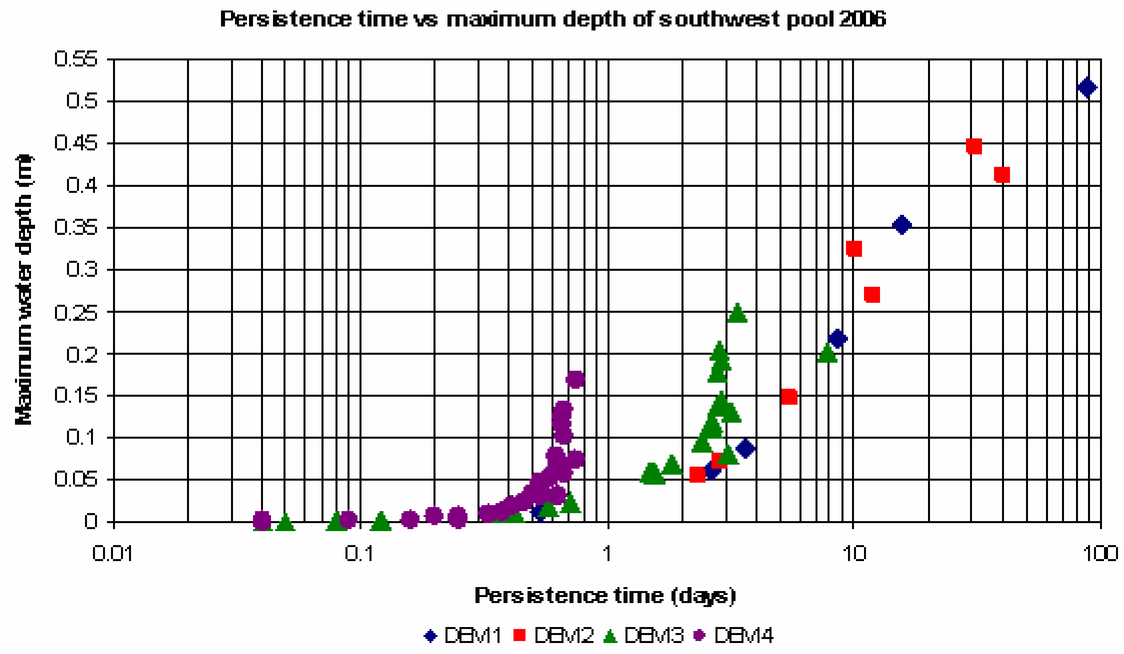

Figure 23: Persistence time and maximum pool water depth for each of the four DEMs in 2006

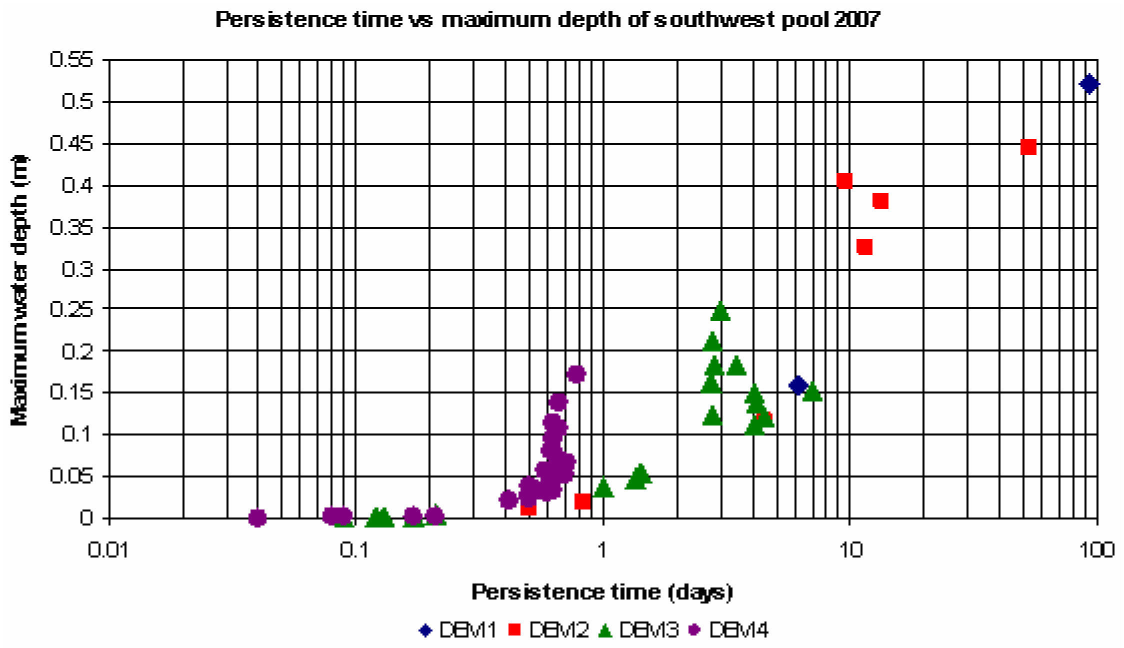

Figure 24: Persistence time and maximum pool water depth for each of the four DEMs in 2007

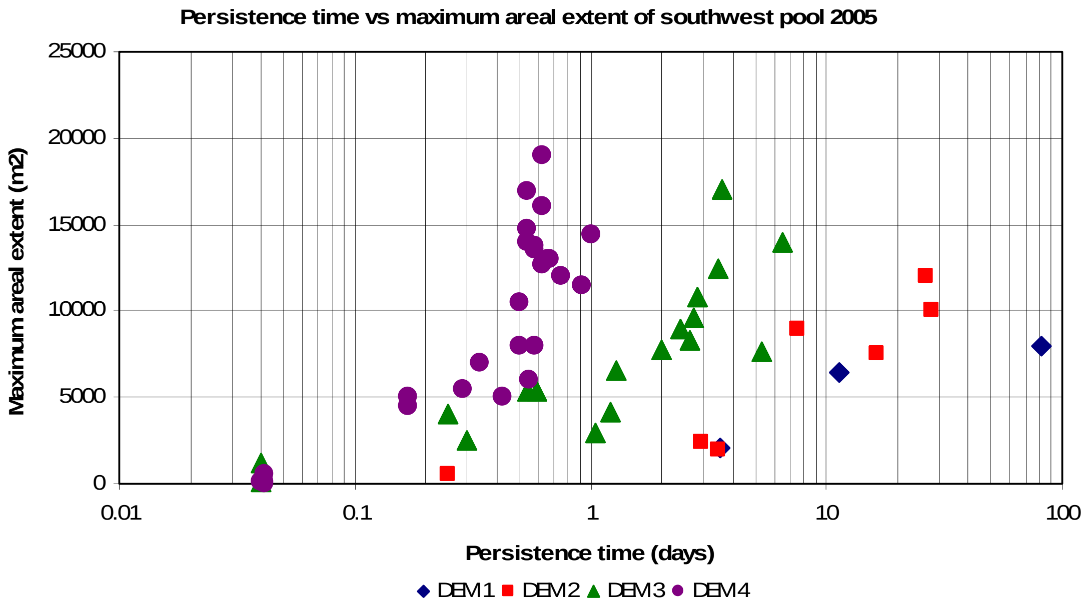

Figure 25: Persistence time and maximum areal extent for each of the four DEMs in 2005

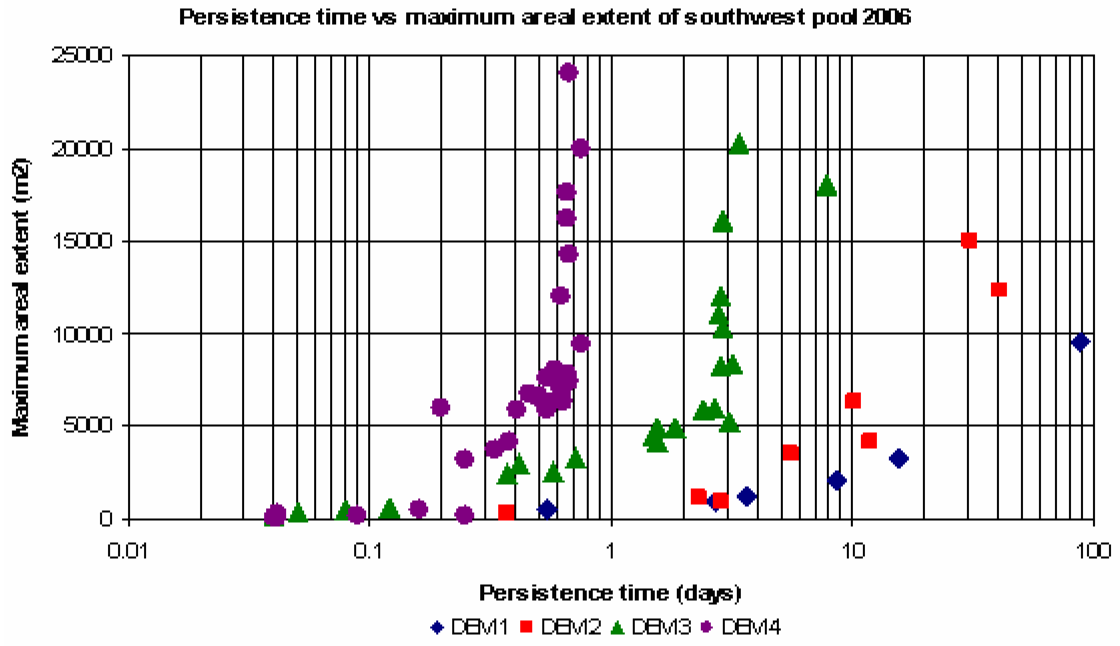

Figure 26: Persistence time and maximum areal extent for each of the four DEMs in 2006

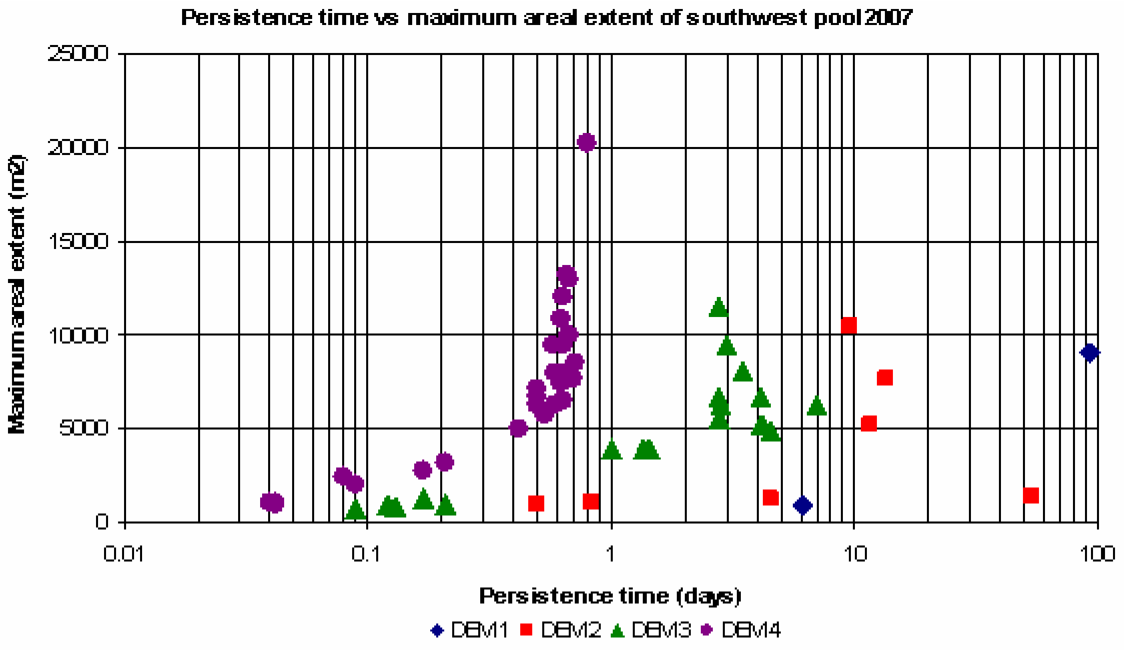

Figure 27: Persistence time and maximum areal extent for each of the four DEMs in 2007

Figure 28, Figure 29 and Figure 30 depict the persistence time and maximum water depth attained in the pool in 2005, 2006 and 2007 respectively for the surface ploughing and hillslope runoff barrier scenarios, as a comparison to the leveling scenarios and existing topography. Figure 31, Figure 32 and Figure 33 show the persistence time and maximum areal extent of each pooling event in 2005, 2006 and 2007 for the surface ploughing and hillslope runoff barrier scenarios, as a comparison to the leveling scenarios and existing topography. The figures are all shown on a log-linear scale. The figures show the impact that each of the various techniques has on the pool's dynamics.

Surface ploughing, creating higher infiltration rates in the surface soils, leads to shorter persistence times and therefore a larger number of pooling events, but does not affect the maximum depth of water reached within the pool. This effect is most pronounced when comparing the existing situation (DEM 1) with the same topography and surface ploughing ('DEM 1 high inf'). With the existing situation, the maximum persistence time of a pooling event is about 90 days. This reduces to about 10 days if surface ploughing is undertaken. Once leveling is implemented (DEM 3), which reduces the maximum water depth attained in the pool from about 50 cm to about 25 cm, the addition of surface ploughing ('DEM 3 high inf') reduces the maximum persistence time of a pooling event from about 8 days to about 4 days. Figures 31, 32 and 33 show that surface ploughing has no significant impact on the areal extent of the pool, as illustrated above, and thus the observed impact on the persistence time is due to the increased infiltration rate and not any change to the pool's dimensions.

Figures 28 through 33 highlight the dramatic impact that the hillslope runoff barrier has on the pool dynamics, by reducing both the maximum water depth attained in the pool and the persistence time of each pooling event and substantially increasing the areal extent of the pool. The maximum persistence time of a pooling event using this technique is only one day in all of the simulation years, with the maximum water depth in the pool not exceeding 15 cm. The very short persistence times and the frequency with which the pool dries out completely using this technique would mean that the pool could not become established as a mosquito breeding habitat. Figure 31, Figure 32 and particularly Figure 33 show that there is some variability in the persistence time of the pool for the same areal extent using the hillslope runoff barrier technique.

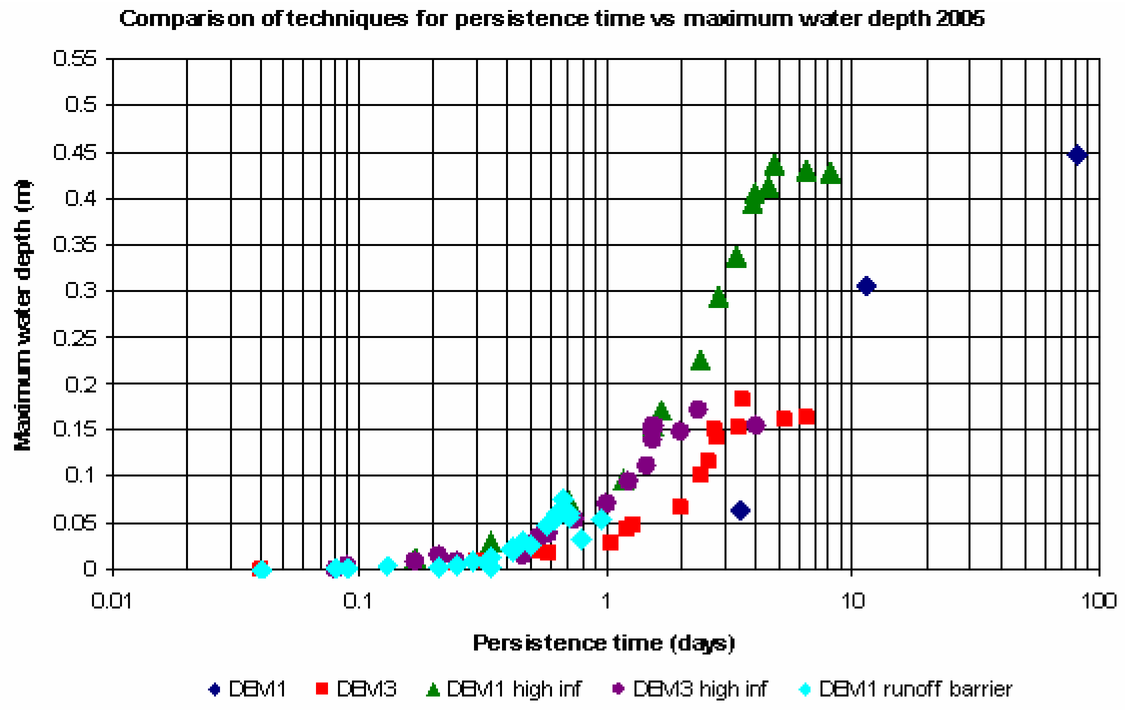

Figure 28: Comparison of persistence time and maximum pool water depth for the surface ploughing and hillslope runoff barrier scenarios in 2005. The existing situation is shown by DEM 1, the existing topography with surface ploughing by 'DEM 1 high inf', levelled topography by DEM 3, leveling plus surface ploughing by 'DEM 3 high inf' and the hillslope runoff barrier by 'DEM 1 runoff barrier'.

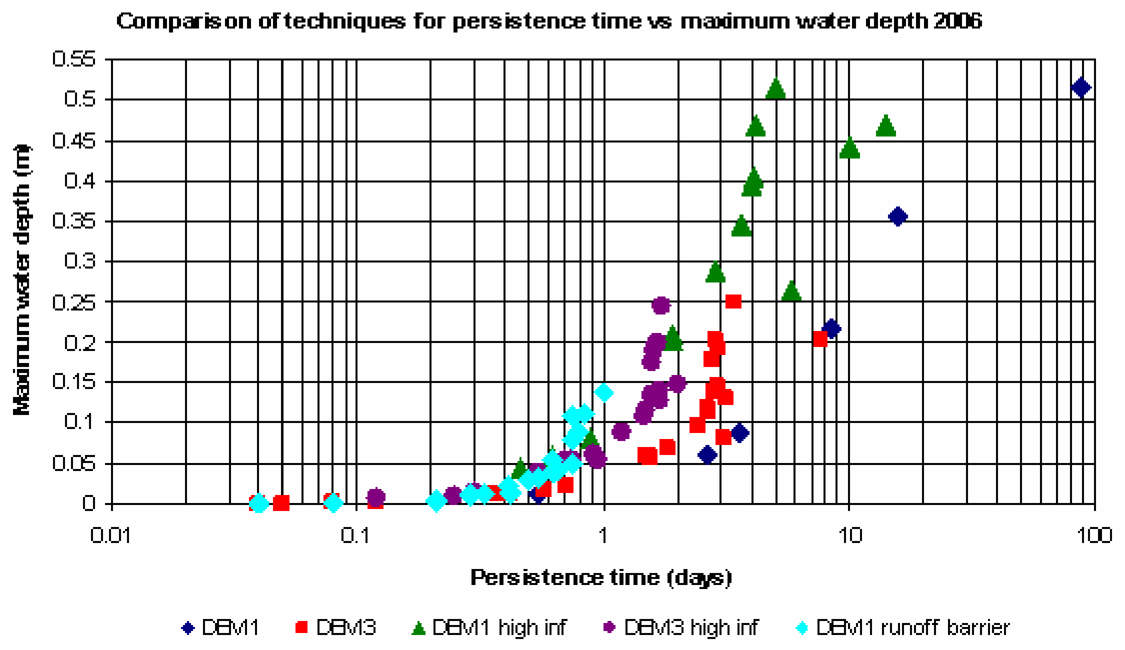

Figure 29: Comparison of persistence time and maximum pool water depth for the surface ploughing and hillslope runoff barrier scenarios in 2006.

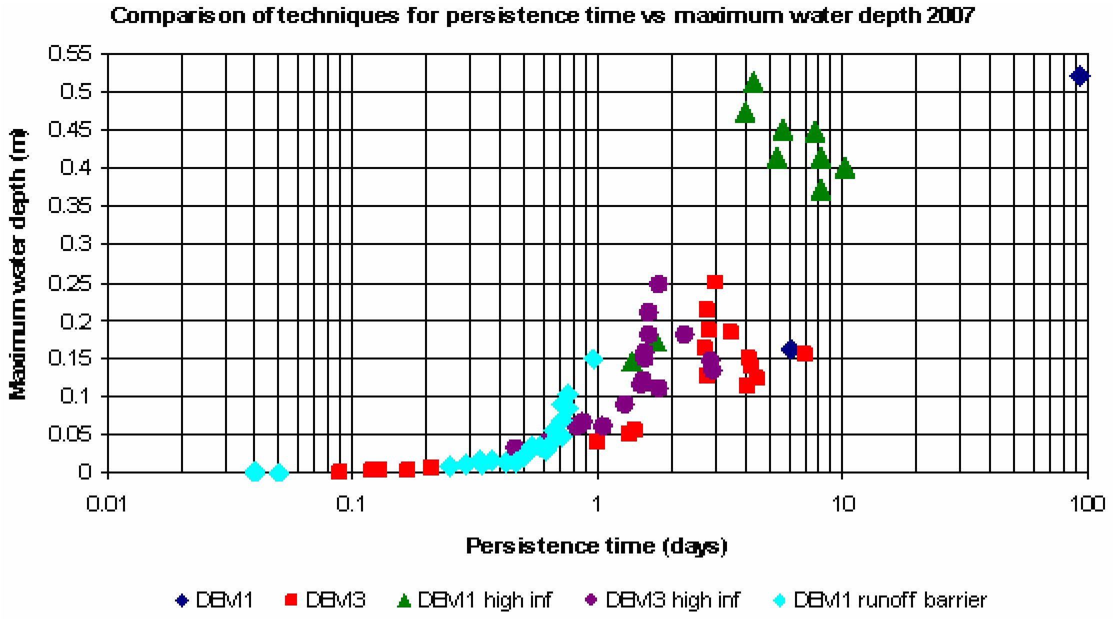

Figure 30: Comparison of persistence time and maximum pool water depth for the surface ploughing and hillslope runoff barrier scenarios in 2007.

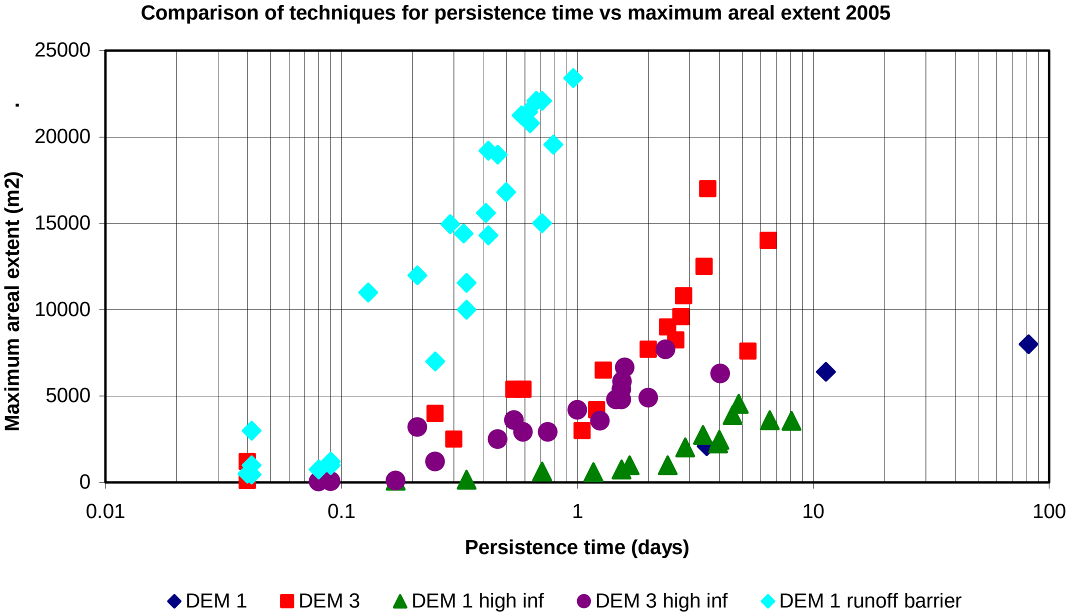

Figure 31: Comparison of persistence time and maximum areal extent for the surface ploughing and hillslope runoff barrier scenarios in 2005

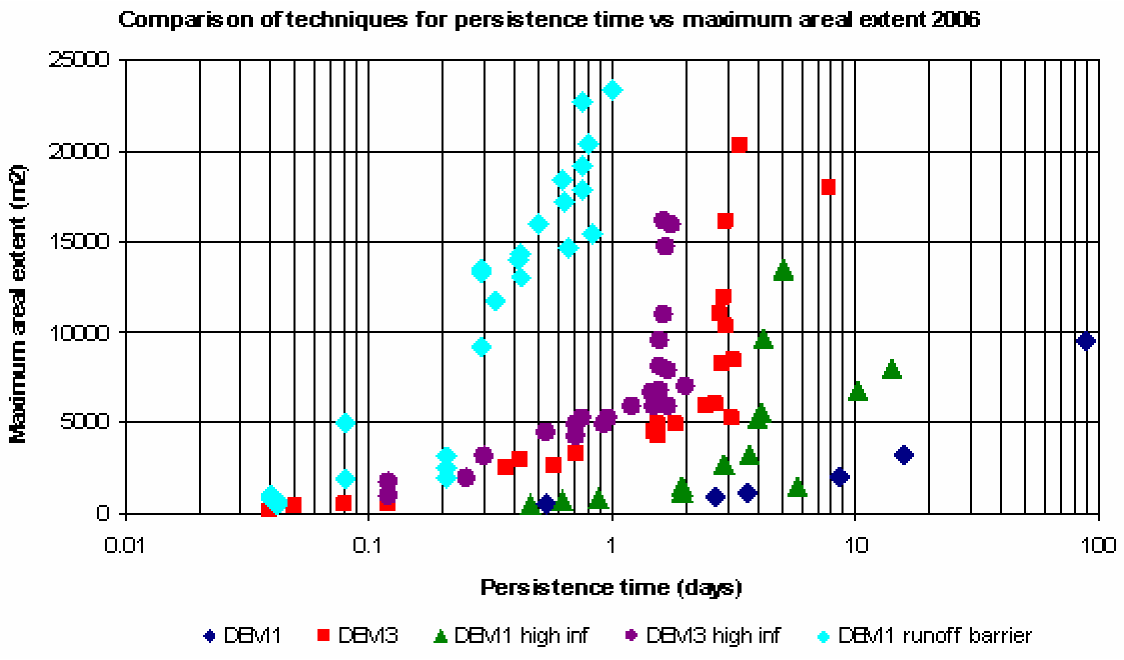

Figure 32: Comparison of persistence time and maximum areal extent for the surface ploughing and hillslope runoff barrier scenarios in 2006

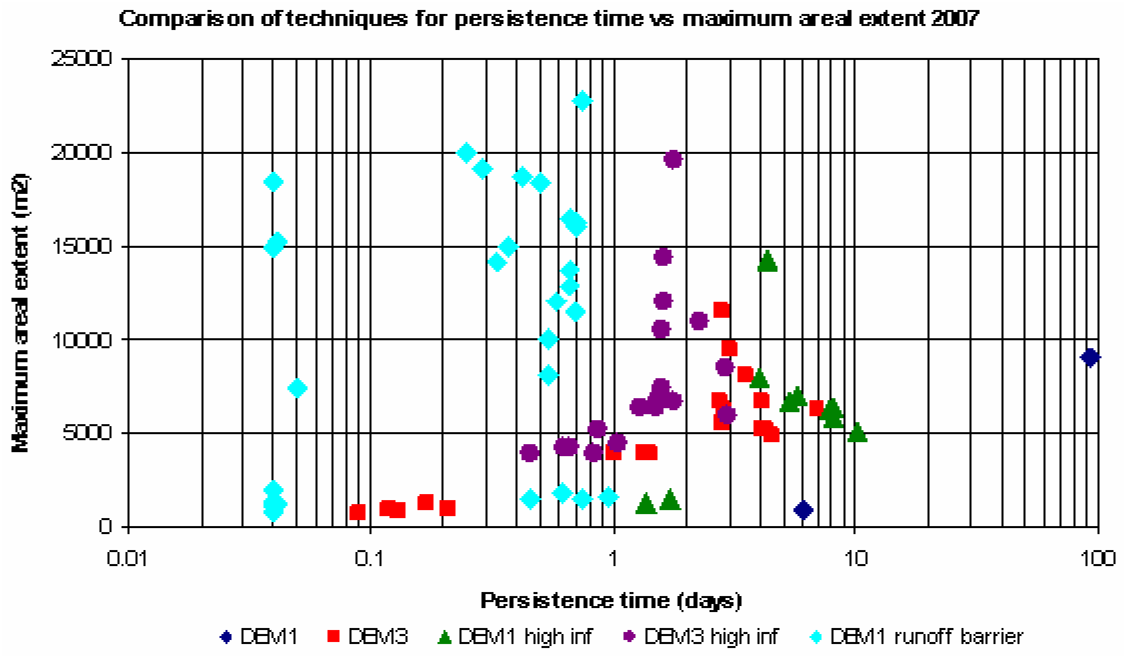

Figure 33: Comparison of persistence time and maximum areal extent for the surface ploughing and hillslope runoff barrier scenarios in 2007

3.5 Discussion

The modeling results show that leveling of the topographic depression where the southwest pool forms has a significant impact on the pool formation characteristics. Shallower topography leads to pools that are more spread out, decreasing the maximum pool depth. The increased areal extent and shallower depth of the pool significantly reduce the persistence time of the pool.

All of the pool formations that resulted from DEM 3 were at or below the critical time for breeding habitat establishment of 7-10 days, which indicates that the extent of leveling represented by DEM 3 (raising the minimum elevation in the centre of the southwest pool by 35 cm) could theoretically result in the removal of this pool as a productive breeding habitat for malaria mosquitoes. However, rainfall can have high inter-annual variability. It would therefore be prudent to level to a slightly greater degree than represented by DEM3, to ensure that the leveling procedure reduced the pool's persistence time sufficiently. DEM4 created pools that had a very short persistence time, but also sometimes created pools that flooded too far downstream. Thus the optimal level for this pool is likely to be between DEM3 and DEM4.

The model results show that ploughing of the surface soils has a large impact on the persistence time of the pool if the topography of the pool basin is left unchanged. This technique by itself could potentially reduce the persistence time of the pool to just over the critical time period required for breeding habitat establishment. However, surface ploughing does not have the same degree of impact on persistence time that topographic leveling does and thus could not guarantee that the pool would not become a breeding habitat. Once leveling has been done, the results indicate that there is little additional benefit from also undertaking surface ploughing. This suggests that efforts should be directed towards carrying out only one of these interventions at a given location and not both, in order to optimally allocate time and resources. Given that topographic leveling appears to have a slightly greater impact, the model results suggest that leveling is the recommended intervention for pools that are of small to intermediate size (where leveling would not demand a burdensome level of time and effort to undertake).

The modeling results suggest that interception of hillslope runoff using some form of barrier could be an extremely effective way to prevent a pool from becoming a mosquito breeding habitat, by significantly spreading out runoff over a large area and reducing the persistence time of the resultant flooding. However, it is very important to note that the diversion of flow in this manner could have significant unintentional impacts, by creating new pools or larger pools elsewhere and effectively changing the location of breeding habitats without providing benefits to the village residents. Additionally, even if flow could be diverted to another location that is further away from the village than the existing pool, there is no way to guarantee that it would not become utilized as a mosquito breeding habitat and that those mosquitoes would not enter the village. If hillslope runoff interception could be undertaken carefully, in a manner that did not transfer the problem to another location around the village, the modeling results suggest that this technique could be the most effective for preventing breeding habitat establishment.

There are costs and benefits to each of the techniques investigated in this study. One logistical advantage of the hillslope runoff barrier is that it can be constructed or upgraded just once per year, in the dry season prior to commencement of rains, and if constructed properly could last through an entire rainy season without further work. However, the construction of a sufficiently robust barrier would take a large number of people and significant time to build, and would also require very careful planning as discussed above. Advantages of the surface ploughing and leveling techniques are that they can be easily undertaken by village residents with minimal equipment and do not require the same expertise in planning – 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. However, surface ploughing 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 season when men are required to be working in the fields and tending to rain-fed crops, which may prove logistically difficult. 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.

The results of this investigation cannot yet be extrapolated to other locations. A water balance assessment of the southwest pool, which has not been undertaken in this analysis, would be needed to confirm that the change in pool volume over time was equal to the sum of inflow into the pool and the volumes leaving the pool through evaporation, infiltration and overflow into adjacent areas. The water balance assessment could also be used to determine how rapidly the model simulated the pool dissipating, which of the two mechanisms for dissipation (evaporation or infiltration) was the dominant mechanism in the model, and to compare these results with published results for similar pools in the region.

A water balance assessment would also be needed to determine the maximum volume of water that can be contained within the pool basin before it overflows and causes downstream flooding. Knowledge of this maximum containable volume and the hypsometric curve of the depression would enable calculation of the flooding area and critical water depth of a pool that needs to be maintained to prevent the pool from overflowing and causing downstream problems. These two pieces of information could then be used to characterize pools and make decisions about management. Two management objectives for these kinds of pools might be to keep runoff contained within a given pool depression and to prevent a pool from becoming established as mosquito breeding habitat. With these objectives in mind, knowledge of the maximum containable volume and hypsometric curve for a given pool basin would enable calculation of the persistence time of the pool under various management strategies, including different degrees topographic leveling and surface ploughing. Pool characterization using the maximum containable volume and hypsometric curve would be required before the intervention methods discussed in this investigation could be extrapolated to other locations.

4. Field Investigation into Efficacy of Neem Extracts

4.1 Methodology

A field investigation was conducted in Banizoumbou village, located in western Niger, approximately 60 km northeast of Niamey (see Figure 1). Neem trees are abundant in the village, with approximately 85 trees within a 500 m radius, but the fruits are not utilized by the residents. This density of neem trees within the village was observed to be typical of villages in the area. The fruiting season is roughly June to August annually. During a rainy season that extends from May to early October and peaks in August, many ephemeral pools form within and around the village in topographic low points. These pools do not form complex aquatic ecosystems and are not utilized by the residents. However, they do provide ideal breeding habitat for *Anopheles gambiae s.l.* mosquitoes, the major local malaria vector. These pools were the targeted areas for neem seed powder applications. There is only one permanent pool of surface water in the village; it is used primarily for cattle watering and is not used by the people.

Environmental variables, including precipitation, temperature, relative humidity and wind speed and direction, and mosquito abundance have been measured in Banizoumbou since June 2005. Two years' monitoring of environmental conditions and vector dynamics, during 2005 and 2006, were used to develop a targeted strategy for the neem seed powder trial in the third year of observations in 2007.

Neem seed powder was prepared and applied following suggestions by Schmutterer (1995) and a reported laboratory trial (Vir *et al.* 1999). Residents of Banizoumbou were asked to collect neem seeds on 5 occasions throughout the rainy season, beginning in mid-July. The residents were familiar with the seeds and where to find them and were able to easily and quickly collect an adequate supply. Due to the abundance of neem trees within the village, an adequate supply of seeds could be gathered mostly from fallen fruit and trees did not have to be stripped of unripe fruit. The fleshy pulp was removed from the outside of the seed casing and seeds were stored either as the bare seed kernel or with the white protective casing around the kernel left intact. Seeds were spread out on grass mats inside a mud brick house to dry for approximately 5-7 days before use.

On the morning of an application day, seeds were crushed into a coarse powder using a mortar and pestle. The mortar and pestle were the same as those used by women in the village for grinding millet and were purchased from a market in Niamey, to avoid appropriating a mortar and pestle currently used for food preparation. The grinding was carried out by a female resident of the village, using the same technique as is used for grinding millet. This methodology required only minimal tools – a grass mat for drying seeds, a mortar and pestle for grinding dried seeds and a bucket for carrying around the powder – that can typically be found within the village. The methodology was designed to be implementable by the village residents and to be sustainable and low cost.

The first application of neem seed powder occurred on 9th July 2007. At that time, only one ephemeral pool was present in the village. After this initial application, the pool dried out and there was no rain for several days. The next application occurred on 20th July 2007, after rain had created some pools in the village, and thereafter applications continued twice weekly until early October 2007, when all pools dried out completely following cessation of rains. This application frequency was chosen to ensure continued efficacy of the powder, due to the short active lifetime of azadirachtin (Schmutterer 1990; Vatandoost and Vaziri 2004).

On each application day, powder was applied to all ephemeral pools in and immediately surrounding the village that were known to be breeding sites for *Anopheles gambiae s.l.* (Figure 1). These ephemeral pools were not observed to establish complex aquatic systems and are not used by the village residents. The powder was carried around in a bucket and liberally sprinkled over the surface of a known breeding pool. The average rate of powder application was approximately 10 g/m^2 of pool surface area, with particular attention paid to pool edges where larvae congregated. No powder was applied to the one permanent pond in the village, which is used as a cattle watering hole. Applications of the neem seed powder in this study were carried out by the author and colleagues from the Eltahir

Research Group and Centre de Recherche Médicale et Sanitaire in Niger, to ensure consistency of application rates and locations.

Mature neem trees are reported to produce approximately 20 kg of fruit per year, of which the seed kernel accounts for 10% of the weight (Vir *et al.* 1999). Therefore the 85 neem trees in Banizoumbou are estimated to produce a total of approximately 170 kg of seed kernel per year, during a fruiting season that coincides with the rainy season and thus presence of ephemeral breeding habitats. At an application rate of 10 g/m^2 of pool surface area, with twice weekly applications for about 12 weeks, the trees in Banizoumbou could cover a total surface area of about 700 m^2 per application. The ephemeral breeding pools in Banizoumbou ranged in size from about 4 m^2 to about 200 m^2 and the quantity of seeds available was sufficient to adequately cover these pools.

The targeted pools were monitored twice weekly. Observations were made of pool presence as an indicator of pool availability. Adult mosquito populations were monitored using CDC miniature light traps deployed at six locations within the village (Figure 1) in the rainy seasons of 2005, 2006 and the intervention year 2007. Light traps were deployed weekly from June to November and monthly during the dry season of December to May. Captured mosquitoes were identified to species at a laboratory of Centre de Recherche Médicale et Sanitaire in Niamey, Niger. Rainfall was measured at hourly intervals from June 2005 with a tipping bucket rain gauge. Temperature and relative humidity were recorded at 15-minute intervals from August 2005 with a Campbell Scientific CR10 datalogger fitted with a temperature and relative humidity probe.

4.2 Results

4.2.1 Anopheline Mosquito Captures

Adult female *Anopheles gambiae s.l.* mosquitoes (Figure 34) in Banizoumbou were first captured in 2007 at the end of July, approximately 2 weeks later than in 2005 and 2006. In all three years, weekly captures increased during July and August from initial weekly captures of single individuals to tens of individuals. Seasonal maximum weekly captures were recorded in late August in 2005 (41 individuals) and in September in 2006 (146 individuals) and 2007 (45 individuals). Weekly captures decreased rapidly to 10 or fewer individuals during late September and early October in all three years. Weekly captures of adult female *An. gambiae s.l.* mosquitoes (Figure 34) during July to September 2007 were generally lower than captures during that same period in 2006, although captures during October and November were comparable in 2006 and 2007. Weekly captures were of similar magnitude throughout the season during 2005 and 2007.

Figure 35 shows the cumulative captures of adult female *An. gambiae s.l.* mosquitoes in each year. Cumulative captures over 2007 (233 individuals) were 49% less than the cumulative captures over 2006 (460 individuals) and 20% greater than cumulative captures over 2005 (193 individuals). Figure 35 shows that more than half of the total cumulative captures in 2006 occurred during September, with weekly captures increasing rapidly during this time. However, in 2005 and 2007, weekly captures remained consistent throughout the season, such that cumulative captures increased at a moderate rate and did not accelerate during the later part of the season as was observed in 2006. Figure 35 also shows that increases in cumulative captures in 2007 were delayed relative to 2006 by about 2 weeks, despite the first rains occurring about 2 weeks earlier in 2007 than in 2006.

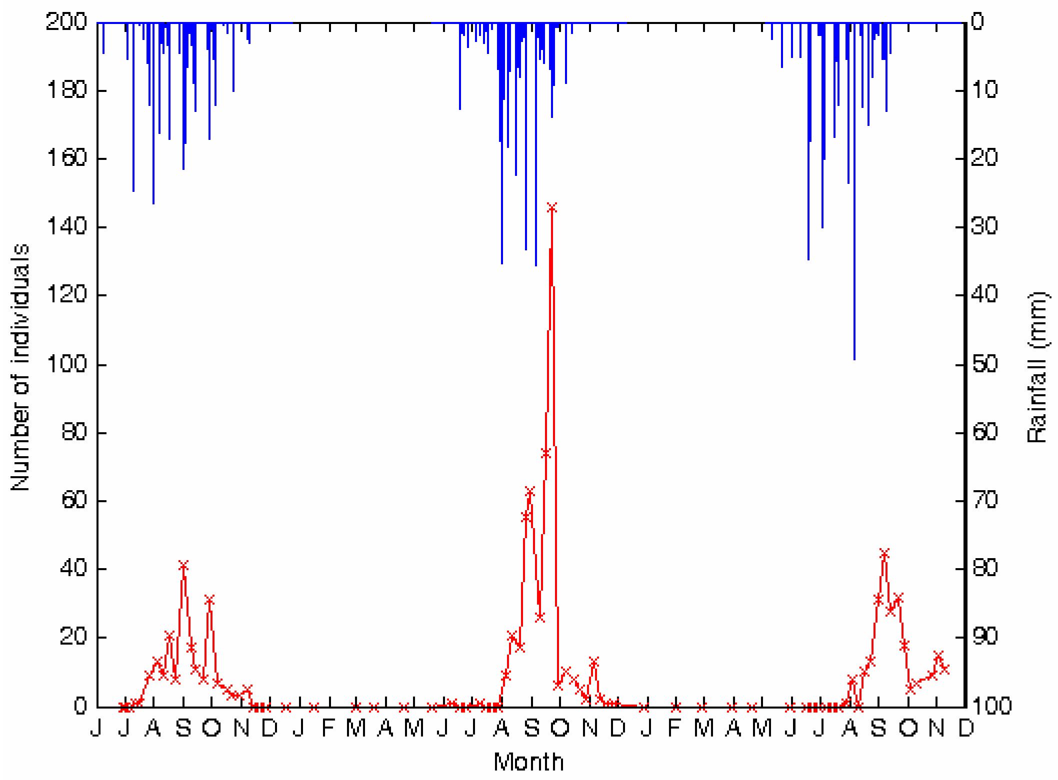

Figure 34: *Anopheles gambiae s.l.* adult female captures and rainfall in Banizoumbou from May 2005 to November 2007. Mosquito captures are shown in red and recorded on the left-hand axis, with crosses to mark the dates of trap deployments. Hourly rainfall measurements are shown in blue and recorded on the right-hand axis.

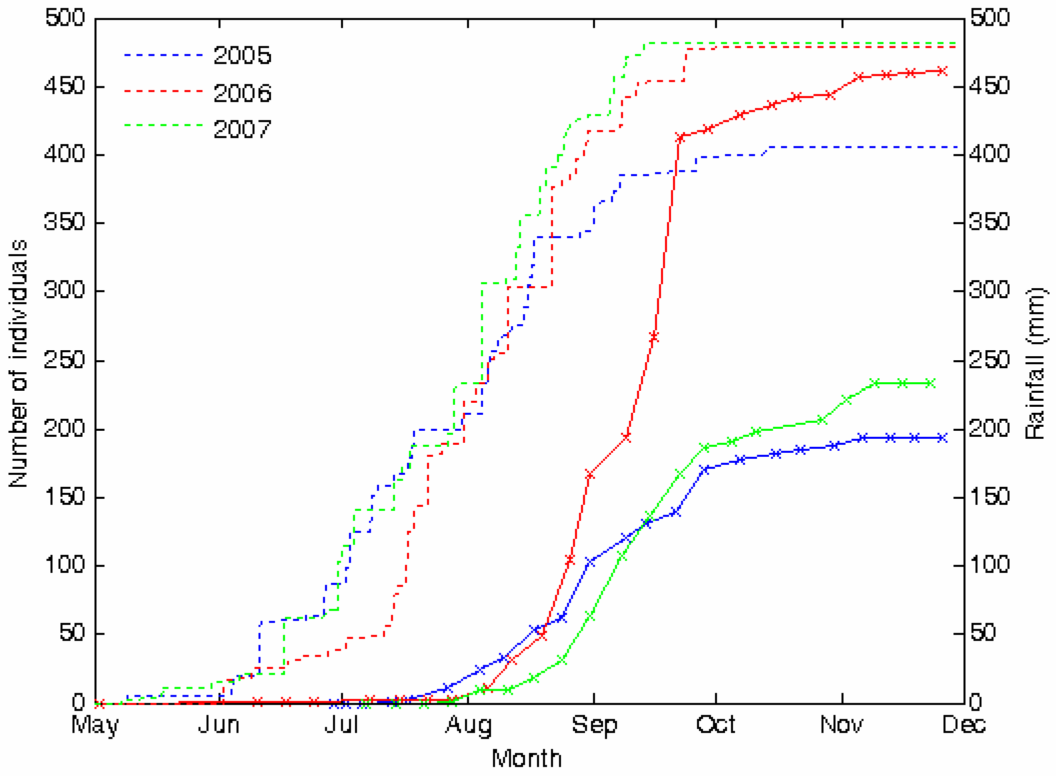

Figure 35: Cumulative *Anopheles gambiae s.l.* adult female captures and rainfall in Banizoumbou during rainy seasons 2005-2007. Cumulative mosquito captures are shown by the solid lines, with crosses to mark the dates of each trap deployment, and the numbers captured are recorded along the left-hand axis. Cumulative rainfall is shown by the dashed lines, updated hourly, and is recorded along the right-hand axis.

4.2.2 Environmental Variables

Environmental variables of rainfall, air temperature and relative humidity were recorded during the non-intervention and intervention years to determine if ambient conditions could have contributed to changes in observed adult mosquito captures.

Figure 34 and Figure 35 show that rain began in Banizoumbou in early- to mid-May in both 2005 and 2007. Rainfall in the early part of the season was similar in both 2005 and 2007. However, there was more rainfall recorded towards the end of the season in 2007 than in 2005, such that total cumulative rainfall in Banizoumbou was 482 mm in 2007, approximately 19% greater than the 405.5 mm measured in 2005.

Figure 34 and Figure 35 show that rain began in Banizoumbou in early June in 2006. Cumulative rainfall measured in 2006 was 478.3 mm, comparable to the 482 mm measured in 2007. Figure 34 and Figure 35 also show that more rainfall fell earlier in the season (May to June) in 2007 relative to 2006, whereas 2006 experienced more rainfall in the later part of the season (August to September) than 2007.

Figure 36 shows daily mean air temperatures (top panel) and daily mean relative humidity values (bottom panel) in Banizoumbou. The data indicate that ambient air temperature and relative humidity observations were similar in 2007 compared with both 2005 and 2006. The average daily mean air temperatures were 29^{o}C in 2005 (standard deviation of 2^{o}C), 30^{o}C in 2006 (standard deviation of 3^{o}C) and 30^{o}C in 2007 (standard deviation of 3^{o}C). Temperatures were higher in the early part of the season (32-34^{o}C in May to June) than in the later part of the season (27-29^{o}C in August to September), as the onset of regular rain events had a cooling effect.

The average daily mean relative humidity values were 44% in 2005 (standard deviation of 18%), 56% in 2006 (standard deviation of 16%) and 59% in 2007 (standard deviation of 15%). Relative humidity values were low in the early part of the season (37-47% in May to June), rose to high levels during the later part of the season when rain events were regular (73-76% in late-July to early-September) and then decreased again after the cessation of rains in November (24-31%).

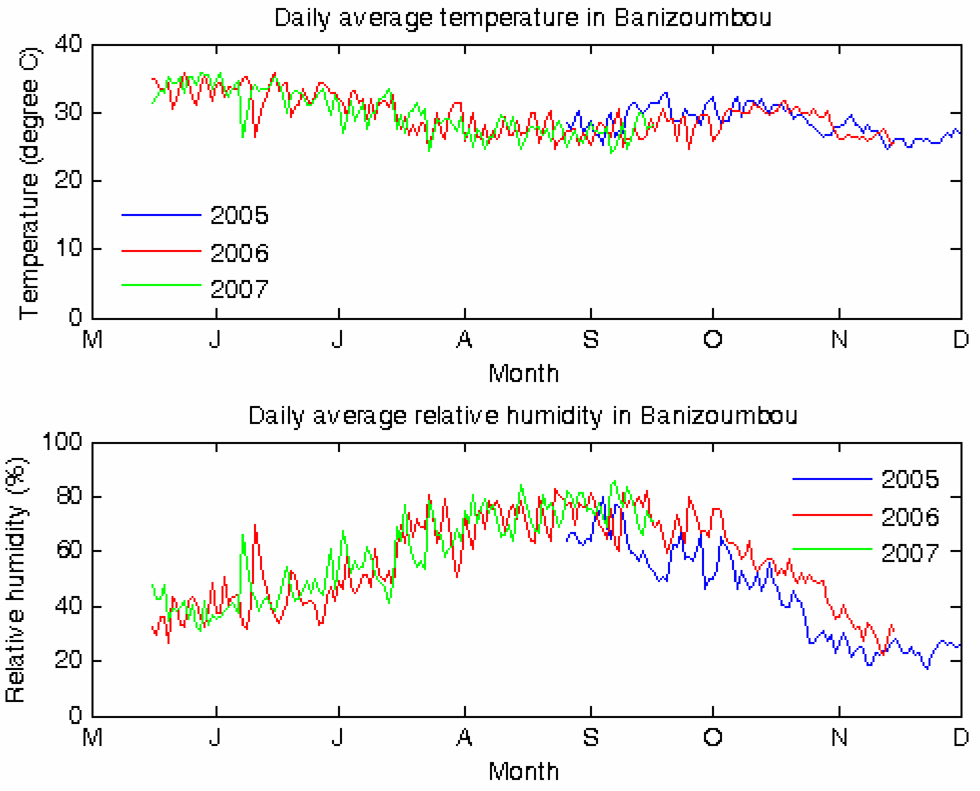

Figure 36: Daily average temperature and relative humidity in Banizoumbou during rainy seasons 2005-2007. Sampling began in August 2005 and measurements were taken continuously at 15-minute intervals until mid-November 2006, when a technical fault led to cessation of data collection for that year. Data was received up until mid-September in 2007, after which a technical fault caused observations to be recorded only during daylight hours. Hence daily average values have not been presented after this time.

4.2.3 Breeding Habitat Availability

Observations of pool persistence were recorded for the ephemeral breeding pools during the non-intervention and intervention years to determine if changes to breeding habitat availability could have contributed to changes in observed adult mosquito captures.

Figure 37 shows the persistence of the central pool (located in the centre of the village on Figure 1) during the period June to November in 2005, 2006 and 2007, measured as the percentage of monitoring visits in each month during which the pool was present. This pool was observed in each year to be the most persistent of the ephemeral pools in Banizoumbou and was also observed to contain the highest abundance of larvae throughout the rainy season. Generally the central pool was absent from October to June and was sporadically present from July to September each year.

Figure 37 shows that the pool was present on more occasions during 2006 and 2007 than in 2005. Averaged over the period July to September, the central pool was present on 69% of monitoring visits in 2005, 92% of monitoring visits in 2006 and 96% of monitoring visits in 2007. The pool was present on more occasions during July in 2007 than in 2006, consistent with the higher rainfall received in the early part of the season in 2007 compared with 2006. The pool was present on fewer occasions during September in 2007 than in 2006, again consistent with the lower rainfall received in the later part of the season in 2007 compared with 2006. Other ephemeral pools shown in Figure 1 were generally less persistent than the central pool, but the relative persistence difference between years was similar to the central pool, with greater persistence during 2006 and 2007 than 2005.

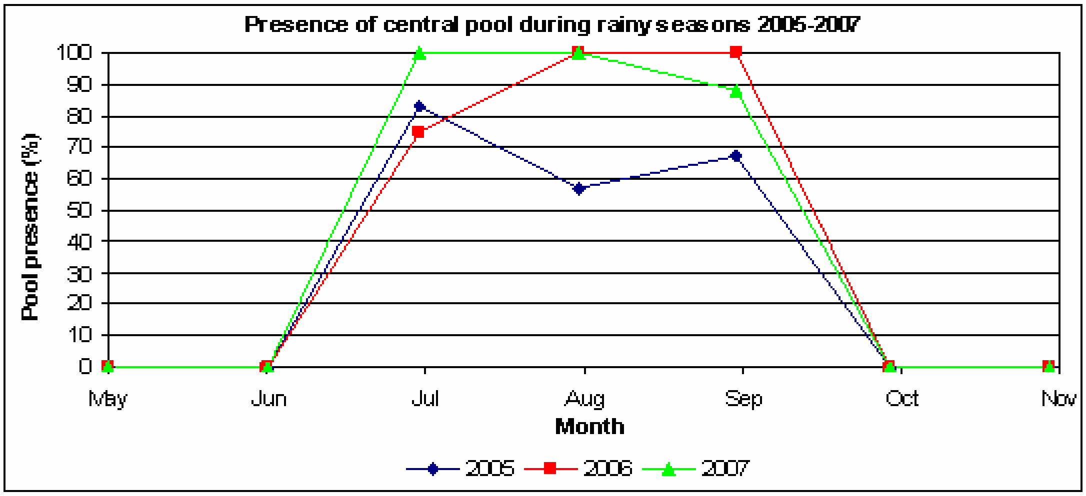

Figure 37: Presence of central pool during rainy seasons 2005-2007. The figure shows the proportion of monitoring events in each month during the rainy seasons of 2005 to 2007 during which the central pool was present as an indication of the persistence of this pool throughout each rainy season.

4.2.4 Culicine Mosquito Captures

Captures of culicine mosquitoes, primarily *Culex sp.* and *Aedes aegypti*, were recorded during non-intervention and intervention years as an indication of any general environmental effects occurring in Banizoumbou that might affect mosquito populations, given that culicine and anopheline mosquitoes share the same ambient environment.

Weekly captures from June to November in 2005, 2006 and 2007 are shown in Figure 38. The top panel shows captures of *Culex sp.* and the bottom panel shows captures of *Aedes* *aegypti* mosquitoes. The figure shows that weekly captures of *Culex sp.* were relatively consistent throughout each season, with little temporal variation and an average weekly capture of 9 individuals in 2005 (standard deviation of 6), 12 individuals in 2006 (standard deviation of 10) and 11 individuals in 2007 (standard deviation of 6). Weekly captures of *Aedes aegypti* mosquitoes showed more temporal variation, with higher captures recorded during August to October in each season than at other times. Average weekly captures of *Aedes aegypti* were 5 individuals in 2005 (standard deviation of 4), 4 individuals in 2006 (standard deviation of 4) and 11 individuals in 2007 (standard deviation of 6). More *Aedes aegypti* mosquitoes were captured during September in 2007 than in 2005 and 2006, but at other times during each season the captures were comparable between years.

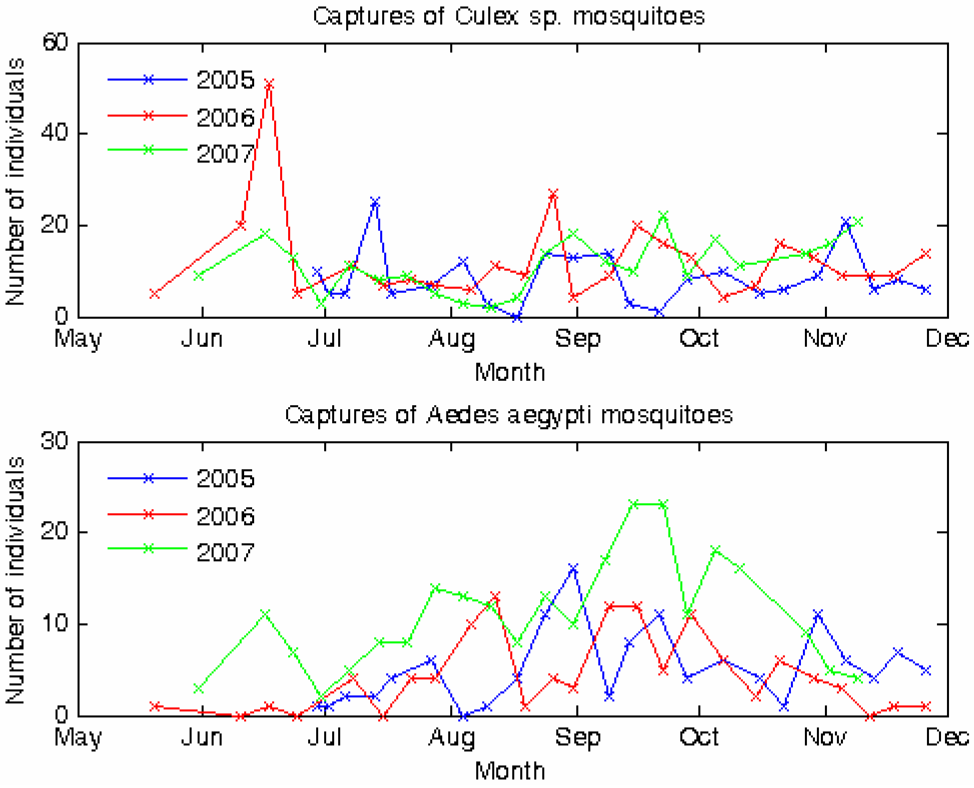

Figure 38: Captures of *Culex sp.* and *Aedes aegypti* mosquitoes during rainy seasons 2005-2007. The figure shows the sum of *Culex sp.* (top panel) and *Aedes aegypti* (bottom panel) captures from all six CDC miniature light traps, for the rainy seasons 2005 to 2007. Sampling commenced June 2005. During the months of June to November, when mosquito population abundance increases, sampling was undertaken on a weekly basis. During the dry season months of December to May, sampling was conducted monthly. Crosses mark the dates of trap deployments.

4.2.5 Relationship Between Rainfall and Anopheline Abundance

Figure 39 shows the relationship between cumulative rainfall and cumulative *An. gambiae s.l.* captures for the intervention and non-intervention years. Data points represent the cumulative rainfall volume at the time of each mosquito sampling event, taken to be the time that deployed traps were collected, for the period June to November in 2005, 2006 and 2007. Cumulative mosquito capture data were ranked in order of increasing cumulative rainfall in each year. For each year, the data points were divided into rainfall bins keeping the same number of cumulative mosquito data points per bin (approximately 6 per bin). The mean and standard deviation of both the cumulative rainfall and cumulative mosquito captures were calculated within each bin for each year. 95% confidence limits were calculated with a t-distribution and are shown as the error bars around each data point. The figure is presented on a log-linear scale.

The figure shows that in 2007, there were about half the number of captured mosquitoes as were captured in 2005 and 2006 for the same quantity of rainfall. The figure shows that the confidence intervals do not overlap between the intervention (2007) and non-intervention years (2005 and 2006), indicating they are statistically different at the 0.05 significance level. The difference between the intervention and non-intervention years is especially noticeable at higher volumes of cumulative rainfall. The figure is depicted on a log-linear axis, so the apparently linear nature of the relationship presented on a logarithmic scale is actually very non-linear. This figure therefore effectively shows that there is a significant difference between the sample means for each binned data point. Therefore the difference of 49% in *An. gambiae s.l.* captures between 2006 and 2007 is significant and indicates that *An. gambiae s.l.* populations were significantly suppressed in 2007.

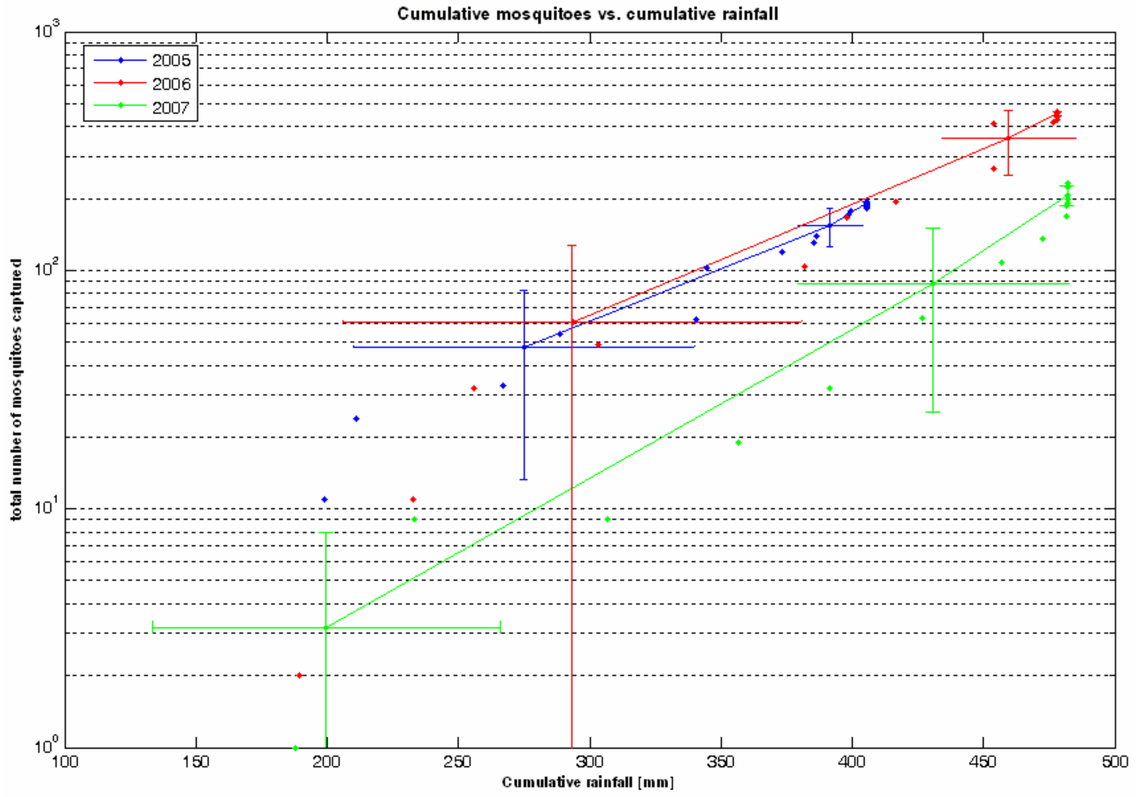

Figure 39: Correlation between cumulative *Anopheles gambiae s.l.* adult female captures and cumulative rainfall in Banizoumbou for 2005, 2006 and 2007. Data points represent the cumulative rainfall volume at the time of each mosquito sampling event, taken to be the time that deployed traps were collected. Cumulative mosquito capture data were ranked in order of increasing cumulative rainfall in each year. For each year, the data points were divided into rainfall bins keeping the same number of cumulative mosquito data points per bin (approximately 6 per bin). The mean and standard deviation of both the cumulative rainfall and cumulative mosquito captures were calculated within each bin for each year. 95% confidence limits were calculated with a t-distribution and are shown as the error bars around each data point.

4.3 Discussion

The relationship between rainfall and *An. gambiae s.l.* abundance is highly non-linear, as shown in Figure 39. The figure also shows that the mosquito response to seasonal rainfall is significantly different after application of the neem extracts in 2007 compared to the corresponding response before application of the neem, in 2005 and 2006.

There are many factors that could potentially influence the populations of *An. gambiae s.l.* mosquitoes in Banizoumbou besides the application of neem seed powder to breeding habitats. The collection of data related to ambient environment, breeding pool availability and culicine mosquitoes was undertaken to determine if these other factors could have affected anopheline mosquito abundance.

The results show that environmental variables of rainfall, temperature and relative humidity were comparable between the non-intervention and intervention years. Rainfall was greater in 2007 compared with 2005, but similar in 2006 and 2007. Given that ambient environmental variables were so similar in 2006 and 2007, it is suggested that these factors should not have significantly affected anopheline mosquito populations in 2007 relative to 2006.

Observations of breeding habitat availability, as indicated by the presence of the pool shown in Figure 37, indicate that availability was greater in 2006 and 2007 than 2005. Habitat availability was comparable in 2006 and 2007 and therefore this should not be a significant factor affecting *Anopheles* abundance in 2007 relative to 2006.

The stability of culicine mosquito populations, during a time when the anopheline mosquito populations were significantly altered, indicates that there was an impact on the mosquito life cycle that only affected the anopheline species. It was observed that, in Banizoumbou, culicine mosquitoes tend to breed in different habitats than *An. gambiae s.l.* and therefore would not have been affected by the neem applications. However, all mosquitoes share the same ambient environment, in terms of temperature, humidity, wind speed and prevailing direction, and populations of human inhabitants. Although the behavior and tolerance to dryness are different for *Aedes aegypti*, *Culex sp.* and *An. gambiae s.l.*, the observed population stability of the culicine mosquitoes over the 3 years shows that there was no major climatic effect on mosquito populations in 2007. Thus the different behavior of *An. gambiae s.l.* in 2007 indicates that anopheline mosquitoes were affected in their breeding habitat. Given that anopheline breeding habitat characteristics were similar between 2006 and 2007, it is argued that the observed difference in *An. gambiae s.l.* abundance in 2007 compared with 2006 is due to the addition of neem seed powder applications.

A comparison of the powder's efficacy with previous studies is difficult as they have been conducted under laboratory or highly controlled field conditions, generally using concentrated neem extracts. The method described used the entire seed and the powder was produced using minimal tools. Field effects such as wind dispersal, dissolution and mechanical mixing from birds and carts would have reduced the impact of the applied powder. It is therefore considered that the neem seed powder performed favorably under true field conditions in this study.

A previous laboratory study has recorded approximately 25% reduction in longevity in adults that were exposed to a neem oil formulation at a concentration of 4 ppm as larvae (Okumu *et al.* 2007). This effect is important as a reduction in average adult daily survival rate is crucial for lowering a vector's disease transmission potential. Although adult longevity was not measured in this study, it is possible that adult longevity was also affected by the applications of neem seed powder and contributed to the observed reductions in *An. gambiae s.l.* abundance in 2007.

Accurate, quantitative data on *An. gambiae s.l.* larval presence in the breeding pools were not collected with sufficient sampling density in space and time to provide quantitative measures of larval abundance. However, it is known that neem seed extracts affect mosquito larvae primarily by inhibiting metamorphosis and suppressing adult emergence (Schmutterer 1995). Therefore it is feasible that a breeding habitat where neem has been applied could exhibit a comparable larval abundance to an unaffected breeding habitat. However, the neem-affected habitat would not be expected to produce as many adult mosquitoes as the unaffected habitat. Hence monitoring of larval abundance may not capture the impact of neem seed powder on mosquito populations. For these reasons, it is considered that monitoring of adult populations is more appropriate for assessing the effectiveness of neem in a field setting than larval abundance.

The techniques used in this study for seed preparation and application could easily be taught to residents and carried out in other villages. The main obstacle to this technique being implemented by residents in other locations is the ability to identify *Anopheles* breeding habitats and thus to appropriately target the applications. This would be particularly important if many pools were present in a village and neem seeds were not sufficient to cover every surface water body. In those cases especially, targeting of powder only to pools that were known to be breeding habitats would be important for efficient use of time and resources. As part of this study, residents of Banizoumbou were educated about the mosquito life cycle, the connection between malaria illness and the ephemeral breeding pools, and the reasons for applying powder to these pools. This kind of education, as well as some training in habitat identification, would be necessary to implement this technique in other locations.

The most significant cost of this method is the labor and time required for collection of seeds, preparation of the powder and application to pools. It is estimated that in Banizoumbou, these tasks would require 3 days per week of labor for one person throughout the transmission season, which lasts about 16 weeks in this region. Using estimates of local daily labor wages, it is anticipated that this intervention would cost about US$200 per year, or roughly US$0.20 per person per year for each Banizoumbou resident. This cost is comparable to the estimated cost of ITNs or other environmental management measures as have been reported in the literature, discussed in Section 2.1 previously.

5. Conclusions

This study of the potential for environmental management techniques to contribute to malaria vector control was focused on the village of Banizoumbou, located in western Niger. Banizoumbou is home to approximately 1000 people and is representative of the many small villages in Sahelian western Niger. The Eltahir Research Group has monitored environmental variables and mosquito abundance in this village since June 2005 and undertaken modeling of the system with the aim of investigating the links between hydrology, the environment and malaria transmission. This study focused on methods that target the larval stages of *Anopheles gambiae s.l.*, the major local malaria vector in western Niger. The environmental management methods investigated were chosen for their suitability to the local environmental conditions and vector dynamics, because they are low-cost and require very little materials or resources, and because they could be carried out by the residents of Banizoumbou in the long-term in a sustainable manner. The study was carried out in two parts: a modeling investigation and a field investigation.

The modeling investigation sought to simulate changes that could be made to the land surface around Banizoumbou village to change the local hydrology, in a way that would negatively impact breeding habitat availability. The investigation used the hydrology component of the coupled hydrology-entomology model developed by Bomblies *et al.* (2008) and represents the first use of this model for the purpose of screening environmental management interventions for malaria control. This part of the study focused on one pool, located to the southwest of Banizoumbou, and investigated three techniques – leveling of the topographic depression where the pool forms, ploughing of the surface soils in the pool basin and constructing a barrier to hillslope runoff in the catchment that feeds the pool.

Results from the modeling investigation showed that:

- Leveling of the topographic depression where the southwest pool forms had a significant impact on the pool formation characteristics. Shallower topography led to pools that were more spread out, decreasing the maximum pool depth and significantly increasing the area over which the pool formed. The increased areal extent and shallower depth of the pool significantly reduced the persistence time of the pool. Raising the base elevation of the pool by about 35 cm reduced the persistence time to less than the time needed for establishment of mosquito breeding, approximately 7 days. Raising the base elevation by 45 cm reduced the persistence time to 1 day, but led to unacceptable levels of flooding in surrounding areas. Therefore the optimal level is considered to be between these two elevations – sufficient to keep the persistence time at or below 7 days but also ensure the pool extent remains confined within the original basin.

- Increasing the surface soil permeability by ploughing also reduced the persistence time of the pool but was not as effective as leveling. Ploughing of the surface approximately doubled the rate at which the pool dissipated compared with the original surface permeability, but had no effect on the depth of water that accumulated in the pool. If the topography of the pool basin was left unchanged, ploughing had a large impact on the persistence time of the pool, but provided little additional benefit if leveling had already been undertaken. Surface ploughing does not have quite the same degree of impact on persistence time that topographic leveling does and thus could not guarantee that the pool would not become a breeding habitat.

- Interception of hillslope runoff using a barrier was demonstrated to be the most effective way to prevent a pool from becoming breeding habitat, by significantly spreading out runoff and reducing the persistence time of flooding. However, diversion of flow in this manner could have significant unintentional impacts, by creating new pools elsewhere and effectively changing the location of breeding habitats without providing benefits to the village residents. Additionally, even if flow could be diverted to another location that is further away from the village than the existing pool, there is no way to guarantee that it would not become utilized as a mosquito breeding habitat and that those mosquitoes would not enter the village. Therefore the use of this technique is only recommended with extremely careful planning and implementation.

- Overall, leveling is considered the intervention most appropriate for general implementation for pools of a small to intermediate size, while ploughing would be recommended for large pools where leveling would require too much work to implement.

- Further work is needed in order to extrapolate these results to other pool locations, both within the village and in other villages. A water balance assessment would have to be undertaken to confirm that the change in pool volume over time was equal to the sum of inflow into the pool and the volumes leaving the pool through evaporation, infiltration and overflow into adjacent areas. A water balance assessment would also be needed to determine the maximum volume of water that can be contained within the pool basin before it overflows and causes downstream flooding. Knowledge of this maximum containable volume and the hypsometric curve of the depression would enable calculation of the flooding area and critical water depth of a pool that needs to be maintained to prevent the pool from overflowing and causing downstream problems. These two pieces of information could then be used to calculate the persistence time of the pool under various management strategies, including different degrees topographic leveling and surface ploughing.

The field work component sought to investigate the efficacy of neem seeds as a larvicide and for inhibiting adult emergence of *Anopheles gambiae s.l.*. The methodology for this technique was designed to be implementable by the village residents and to be low cost. Neem seed powder was applied regularly to all pools within and immediately surrounding the village that were observed to contain anopheline larvae, with the exception of the one permanent pool in the village that is used for cattle watering. This field investigation represents the first field trial of neem seed extracts produced locally and applied at the village scale over the length of a malaria transmission season.

Results from the field investigation showed that:

- Cumulative captures of adult female *Anopheles gambiae s.l.* mosquitoes over 2007 (233 individuals) were 49% less than the cumulative captures over 2006 (460 individuals) and 20% greater than cumulative captures over 2005 (193 individuals). In 2005 and 2007, weekly captures remained consistent throughout the season, such that cumulative captures increased at a moderate rate and did not accelerate during the later part of the season as was observed in 2006. Increases in cumulative captures in 2007 were delayed relative to 2006 by about 2 weeks, despite the first rains occurring about 2 weeks earlier in 2007 than in 2006.

- Rainfall in the early part of the season was similar in both 2005 and 2007. However, there was more rainfall recorded towards the end of the season in 2007 than in 2005, such that total cumulative rainfall in Banizoumbou was 482 mm in 2007, approximately 19% greater than the 405.5 mm measured in 2005. Cumulative rainfall measured in 2006 was 478.3 mm, comparable to the 482 mm measured in 2007. The relationship between cumulative rainfall and cumulative *Anopheles gambiae s.l.* captures was highly non-linear and shown to be significantly different in 2007 than in 2005 and 2006.

- Ambient air temperature and relative humidity observations were similar in 2007 compared with both 2005 and 2006. Pools where neem seed powder was applied were generally more persistent in 2006 and 2007 than in 2005, due to the greater volumes of rainfall in those two years. Weekly and cumulative captures of *Culex sp.* and *Aedes aegypti* mosquitoes throughout the 2007 season were similar to those captured in 2005 and 2006.

- Given the comparability between 2006 and 2007 of all the observed data, a similar *An. gambiae s.l.* abundance could have been expected in 2007 as in 2006. Similarly, the observed differences between 2005 and 2006 would have been expected to repeat in 2007. However, the data shows that *An. gambiae s.l.* populations were suppressed relative to expectations in 2007. The only significant change made in 2007 was the application of neem seed powder to *An. gambiae s.l.* habitats and therefore it is suggested that the observed difference in *An. gambiae s.l.* abundance in 2007 can be attributed to the neem seed powder.

- In summary, neem seeds could provide an appropriate, sustainable larvicide for the malaria vector *An. gambiae s.l.* in the Sahel region of Niger and adjacent areas having similar environmental characteristics and vector dynamics. Although this method will not replace other forms of malaria abatement in Africa, it is suggested that neem seed powder could be a useful additional tool in the fight against this disease.

- A larger-scale study is recommended to test the efficacy of this method in other, similar villages in the region, incorporating control villages as well as multiple test villages. A multi-year trial is also recommended to test for any long-term residual effects of using the powder and to determine if its efficacy is sustained during rainy seasons with different climatic and environmental conditions.

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