Reg Environ Change (2013) 13:509–519
DOI 10.1007/s10113-012-0287-4

ORIGINAL ARTICLE

Options for water storage and rainwater harvesting to improve health and resilience against climate change in Africa

Eline Boelee · Mekonnen Yohannes · Jean-Noël Poda · Matthew McCartney · Philippe Cecchi · Solomon Kibret · Fitsum Hagos · Hammou Laamrani

Received: 21 December 2010 / Accepted: 29 January 2012 / Published online: 25 February 2012

Abstract West and East Africa experience high variability of rainfall that is expected to increase with climate change. This results in fluctuations in water availability for food production and other socioeconomic activities. Water harvesting and storage can mitigate the adverse effects of rainfall variability. But past studies have shown that when investments in water storage are not guided by environmental health considerations, the increased availability of open water surface may increase the transmission of water-related diseases. This is demonstrated for schistosomiasis associated with small reservoirs in Burkina Faso, and for malaria in Ethiopia around large dams, small dams, and water harvesting ponds. The concern is that the rush to develop water harvesting and storage for climate change adaptation may increase the risk for already vulnerable people, in some cases more than canceling out the benefits of greater water availability. Taking health issues into account in a participatory approach to planning, design, and management of rainwater harvesting and water storage, as well as considering the full range of water storage options would enable better opportunities for enhancing resilience against climate change in vulnerable populations in sub-Saharan Africa.

Keywords Water storage · Health · Climate change · Africa · Small reservoirs · Water harvesting

E. Boelee (✉)
International Water Management Institute (IWMI),
Colombo, Sri Lanka
e-mail: e.boelee@waterhealth.nl

M. Yohannes
Mekelle University, Mekelle, Ethiopia

J.-N. Poda
Institut de Recherche en Sciences de la Santé (IRSS),
Centre National de la Recherche, Scientifique et Technologique (CNRST), Ouagadougou, Burkina Faso

M. McCartney · F. Hagos
International Water Management Institute (IWMI),
Addis Ababa, Ethiopia

P. Cecchi
Institut de Recherche pour le Développement (IRD),
IRD UMR G-EAU, Montpellier, France

S. Kibret
Addis Ababa University, Addis Ababa, Ethiopia

H. Laamrani
International Development Research Centre (IDRC),
Cairo, Egypt

Introduction

Rainwater harvesting and water storage as climate change adaptation

The economy and livelihood systems of West and East Africa depend heavily on rainfall. However, both regions experience highly variable rainfall that is expected to increase with climate change (Thornton et al. 2006). Climate change in sub-Saharan Africa will exacerbate current climate variability, so that water resource planners and managers will have to work with increasing uncertainty. Current scenarios predict that climate change will increase water scarcity in many places. Coupled with increased populations, 75–250 million people in sub-Saharan Africa will experience increased water stress by 2020 (IPCC 2007).

Water harvesting and storage are important mechanisms for adapting to climate change. These interventions promote economic growth and help alleviate poverty by reducing risk and making water available when and where it is needed (Braune and Xu 2010). Recent studies suggest that in Africa and globally, soil storage enhancement and small-scale runoff harvesting can make a useful contribution to agricultural productivity under current and future climates (Rockstrom et al. 2009; Vohland and Boubacar 2009; Wisser et al. 2010). Rainwater harvesting is an age-old practice, applied for domestic water supply and for agriculture. Such water systems include domestic systems for single households and small communities, on-farm (in situ) water conservation systems, small surface reservoir systems for smallholder irrigation, livestock watering and domestic water use and large surface dam systems for large-scale irrigation, hydropower production, industrial and domestic water supply (Fig. 1). Each type has its own challenges at the various scales related to design, use, governance (ownership and maintenance), and environmental impacts (Johnston and McCartney 2010).

To date, in Africa, there has been little systematic analysis of how climate change may affect existing water storage, how water storage can increase resilience to climate change, or how to account for climate change in the planning and management of new water storage schemes. In many African countries, water and agricultural management, and development planning are severely constrained by the lack of financial and human resources, while with increasing climate variability, the need for water storage is growing. Ill-conceived water storage schemes may not deal well with the consequences of climate change. At best, this would mean current investments are a waste of money, diverting scarce financial resources away from other more beneficial investments. At worst, it may mean that they aggravate the negative impacts of climate change, possibly including adverse health impacts.

The objective of this paper is to highlight how adaptation strategies involving rainwater harvesting and water storage must incorporate health considerations if these are to enhance resilience. It aims to assist decision makers in Africa help vulnerable populations adapt to increasing climate variability by providing an introduction to participatory health impact assessment (PHIA) and concrete examples of mitigating measures. Our paper draws on field studies by the authors on schistosomiasis in Burkina Faso and malaria in Ethiopia associated with rainwater harvesting and water storage. After an introduction to water-related health risks, the two countries are introduced, as well as the principles of PHIA. The methodology section explains how the field data were collected and analyzed. The results and discussion section presents the findings from Burkina Faso and Ethiopia related to international references, which are then applied in PHIA, and in recommendations on how to mitigate health risks associated with adaptations to water stress.

Relevant water-related health risks

The overall burden of disease in sub-Saharan Africa is higher than anywhere else in the world (WHO 2008). Globally, some 10% of the total disease burden is associated with water; for sub-Saharan Africa, the percentage is more than double (Table 1) and most of these will be negatively affected by climate change (McMichael et al. 2006; Confalonieri et al. 2007). However, while it is very hard to quantify the various impacts of increased climate variability on human health, the negative impacts of climate change are most likely to be worst in countries with relatively weak public health systems, hitting the most vulnerable populations hardest (Patz et al. 2005, 2007).

Water-based diseases (e.g., guinea worm and schistosomiasis) and water-related insect-borne diseases (e.g., malaria, dengue fever, river blindness, yellow fever, and filariasis) are transmitted through either insect vectors or intermediate hosts, which spend some or all of their lives in

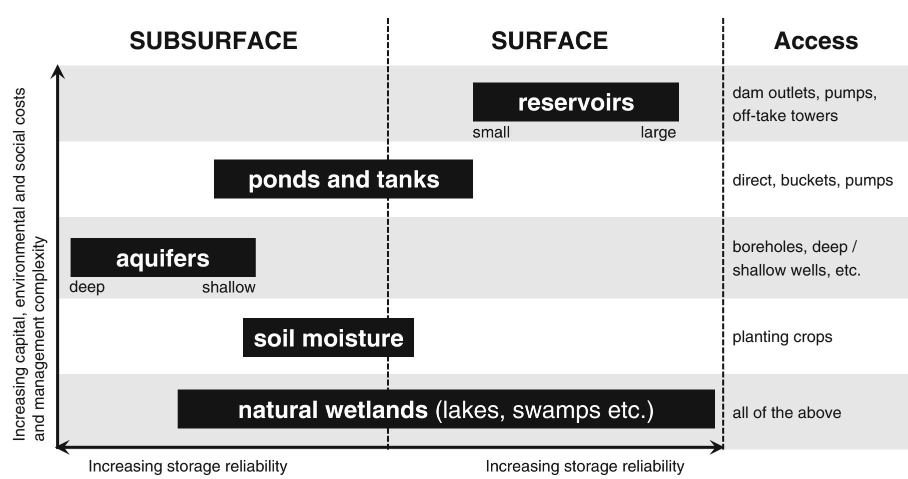

Fig. 1 Continuum of water storage framework

Table 1 Annual DALYs (in thousands) lost globally for health risks associated with drinking water, sanitation, hygiene, and water resource management (after WHO 2008)

Health risk	Global	Africaa
Diarrheal diseases	72,777	32,203
Malnutrition	17,462	7,095
Intestinal nematode infections	4,013	1,528
Lymphatic filariasis	5,941	2,263
Trachoma	1,334	601
Schistosomiasis	1,707	1,502
Malaria	33,976	30,928
Drowning	10,728	1,824
Other (dengue fever, Japanese encephalitis, onchocerciasis, and combinations)	1,740	384
Total water-related	149,678	78,328
Total DALYs	1,523,259	376,525
% Water-related	9.8	20.8

The disability adjusted life year (DALY) can be thought of as one lost year of "healthy" life, and the burden of disease can be thought of as a measurement of the gap between current health status and an ideal situation where everyone lives into old age, free of disease, and disability (WHO 2008)

[a] Low- and middle-income countries only

water. Many open water storage facilities, including reservoirs, ponds, and tanks, may provide ideal breeding conditions for mosquitoes, flies, or snails, bringing both the vectors and the disease closer to people (Erlanger et al. 2005; Keiser et al. 2005; Steinmann et al. 2006). Water depth, soil, temperature, presence of aquatic vegetation, predators, chemical composition of the water, but also human activities determine the suitability of water bodies as vector habitats. Whether or not rainwater harvesting and subsequent water storage lead to increased transmission of water-based or insect-transmitted diseases depends on the inter-linkages between a range of factors related to the local climate, agroecosystem, and human interventions and behavior. This in turn will determine if the risk of disease transmission becomes a real threat to human health.

Schistosomiasis is a water-based helminthic disease, with snails as intermediate hosts that is transmitted via water contact. In 2004, some 1.7 million DALYs were lost due to schistosomiasis globally, killing 41,000 people—36,000 in sub-Saharan Africa, where 88% of the DALYs were lost (WHO 2008). The disease exists in various forms that each have their own specific snail host and habitat requirements. The ecology of these snails and with that, transmission of the disease, are both strongly related to water use patterns as well as human hygiene. Water resources development can increase the number of breeding sites for intermediate snail hosts of schistosomiasis as well as other risk factors (Boelee and Madsen 2006).

In 2009, malaria worldwide infected 225 million people, of which 781,000 died (WHO 2010). Because of extensive control efforts in many countries, this morbidity is decreasing steadily from the 889,000 deaths in 2004 (WHO 2010). Malaria is transmitted by *Anopheles* mosquitoes, and each species has its own specific larval habitat requirements and specific biting behavior in terms of time, place, and host. The right combination of temperature, humidity, a vulnerable human population, and the parasite has to occur in conjunction with suitable habitat.

Burkina Faso

The rainfall pattern in Burkina Faso is characterized by a strong gradient, varying from below 500 mm in the north to over 1,000 mm in the south, where the wet season is also longer. The year-to-year variability is high (Sultan and Janicot 2000). There appears to be a trend toward a decrease in precipitation since 1970 (L'Hôte et al. 2002). At the same time, as a consequence of land-use change, the runoff coefficient has increased from 1.5 to 3.0% in the northern part of the Nakambé (White Volta) Basin, resulting in increased discharge despite reduced rainfall (Mahé et al. 2005). Floods are very violent and cause severe and recurrent damage to hydraulic infrastructure, particularly dikes and bridges. Spatio-temporal variability and recurrence of extreme events (excessive rains or inversely drought periods) seriously constrain efforts to intensify rain-fed agriculture and livestock breeding, which currently represent more than two-thirds of the domestic production of Burkina Faso. These constraints are likely to get worse with the projected 3–3.5°C increase in temperatures (IPCC 2007; Thornton et al. 2011).

Water reservoirs make up a considerable part of the surface water retention in Burkina Faso, particularly in areas where the flows are seasonal and during the dry season, when other water resources have dried up. The geology of most of the country partly comprises weathered granite rocks with little water-holding capacity. Several large dams have been constructed in Burkina Faso, initially for the generation of electricity, but currently also used for fishing, urban water supply, and irrigation of rice, cotton, maize, sorghum, and horticulture (Direction Générale des Ressources en Eau (DGRE) 2000, unpublished). Particularly, since the major drought in 1973/74, many small reservoirs were constructed in the country to secure human and animal water supply (Comité Inter Africain d'Etudes Hydrauliques (CIEH) 1985, unpublished). There are around 1,700 small reservoirs that are used for industrial production, urban energy, fishing, and horticulture, while also serving to recharge groundwater for drinking water supply. Many reservoirs play an important role in climate change adaptation by preventing flooding while storing excess water far into the dry season. However, around many small reservoirs, crowding, poor sanitation, organic water pollution, and intense water contact coincide with the presence of the helminths, leading to increased transmission of schistosomiasis (Boelee et al. 2009). Approximately a quarter of the population is infected by schistosomiasis, mainly caused by *Schistosoma haematobium* (Clements et al. 2009). Mass treatment at schools has locally been highly successful in reducing prevalence and intensity of infection (Touré et al. 2008).

Lemoalle and de Condappa (2009) simulated climate change scenarios for the Volta basin to determine impacts on the capacity of the Volta Lake in Ghana. A 2°C increase in temperature would only slightly modify the current situation, while changes in the rainfall pattern would have much greater impacts. In the dry scenario, the Volta Lake's water level would drop below the minimum operating level, making hydropower generation impossible. In the wet scenario, water levels came close to the maximum. The authors also simulated an increase in the number of small reservoirs in the Upper Volta Basin in Burkina Faso. With a steady annual growth rate of 10%, the number of small reservoirs would be 7 times higher in 2020 than in 2000. This, probably unrealistic, growth rate would result in a 3% reduction in inflows to the lake, a small impact on hydropower production as compared to the present variability in the stored volume or to the possible consequences of climate change (Lemoalle and de Condappa 2009).

Ethiopia

Most of Ethiopia consists of high plateaus and mountain ranges. The agricultural potential of Ethiopia is largely unexploited with less than 40% of the arable land currently under cultivation. Most cultivation takes place in the highlands that are characterized by a highly fragile natural resource base. Soils are often coarse-textured, sandy, and inherently low in organic matter and water-holding capacity, making them easily susceptible to both wind and water erosion. Hence, crops can suffer from moisture stress and drought even during normal rainfall seasons. Farm productivity is low and declining, while farmers find themselves increasingly poor and vulnerable. Water resources are underdeveloped, and many challenges must be confronted before water resources can be better utilized and productivity enhanced (Awulachew et al. 2005). Climate change is projected to lead to increases in temperature between 3 and 3.5°C, while rainfall patterns are hard to predict with the high variability between seasons in different parts of the country (IPCC 2007).

In the past decades, several large dams have been constructed in Ethiopia. The Koka dam in the Central Rift Valley (annual rainfall 800 mm) was built originally for hydropower but now also supplies water to downstream irrigation schemes. The construction of small dams started in the 1990s after recurrent droughts. These supply water for domestic use and irrigation to enhance household food security. By 2001, more than 40 small dams were constructed in the Tigray Region (750 mm rain), with storage capacities ranging from 0.1 to 3.1 million m^3. Where large dams are mainly fed from rivers, small reservoirs also receive substantial amounts of runoff, sometimes leading to rapid siltation (Tamene et al. 2006). In the last 10–15 years, some 150,000 water harvesting ponds have been constructed throughout the country, but especially in Oromia, Amhara, Tigray, and Southern Regions (Awulachew et al. 2005). Many problems have been reported on the technical functioning of these ponds as well as on their environmental sustainability (Johnston and McCartney 2010). Ponds and other types of water harvesting in Ethiopia have also enhanced the availability of suitable habitat for *Anopheles* mosquitoes and led to increased transmission of malaria (Ghebreyesus et al. 1999; Waktola 2008; Yohannes and Haile 2010). Around 56 million people in Ethiopia are at risk from malaria, of which 22.5 million live in areas of high (>1 case per thousand) transmission. Control efforts are mainly based on the distribution of insecticide-treated bed nets and indoor residual spraying, resulting in a reduction in the number of reported deaths from malaria since 2005 (Ministry of Health 2009, unpublished).

Adapted participatory health impact assessment (PHIA)

Agricultural water storage development can be guided by national policies, but with the exception of large dams, the implementation often occurs in an ad-hoc fashion. For large-scale water resources development, usually formal environmental impact assessments (EIA), with or without additional or incorporated health impact assessments (HIA; Birley 1995; Fehr 1999), are required by governments and funding agencies. However, environmental or health issues are rarely considered in the planning and design of smaller water interventions, since it is not economically viable to conduct formal impact assessments for many small structures. Nevertheless, more systematic planning could help to prevent the negative health impacts of water storage and enhance the benefits for increased resilience against climate change. In Morocco (Boelee and Laamrani 2004) and Ethiopia (Yohannes et al. 2005), participatory approaches led to increased awareness and community action for environmental disease control around water impoundments. In many parts of the world, particularly in sub-Saharan Africa, capacity for HIA is limited and working in a participatory way with interdisciplinary teams and local users remains uncommon.

Materials and methods

Approach

The field studies, comprising both ecological and epidemiological investigations, focused on malaria in Ethiopia and schistosomiasis in Burkina Faso. The studies in Ethiopia were carried out (1) at 13 villages between 1,700 and 1,900 m altitude around the large Koka dam reservoir in the central Rift Valley in 2006 and 2007, and (2) on various types of water harvesting structures throughout the northern Region of Tigray in 2004 and 2005. In Tigray, 5 villages with rainwater harvesting ponds and wells were compared to 5 nearby villages without ponds; and 2 villages with nearby in situ rainwater harvesting structures, mostly in the shape of half-moons near trees and as ditches along the contour lines of the fields, were compared to 2 control villages where the ditches were located far away from the houses. In Burkina Faso, 27 villages with small reservoirs and 11 without were studied between 1985 and 2006 throughout the country. Based on insights gained from these field studies and earlier experiences by the authors, PHIA for community-managed water storage has been developed.

The results presented in this paper synthesize key findings from the field studies and underpin the discussion of PHIA later in the paper. The storage continuum framework and findings from Ethiopia and Burkina Faso were complemented with climate change considerations and extrapolated to general health risks, for which recommendations were developed for improved planning and implementation of rainwater harvesting and storage of water for agriculture in sub-Saharan Africa.

Sampling methods

At all study sites, all types of water bodies, such as reservoirs, canals, drains, seepage areas, fields, and puddles, were identified, mapped, and checked for the presence or absence of mosquitoes and freshwater snails. In Ethiopia, mosquito larvae were sampled quantitatively with standard dippers (350 mm). Larvae were preserved and classified by genus, while *Anopheles* larvae, found in 206 sites near Koka, in 80 ponds and 61 in situ rainwater harvesting structures in Tigray, were identified by species. In Burkina Faso, snails were sampled quantitatively using a drag scoop in deep water bodies and 0.1 m^2 quadrates in shallow habitats. *Bulinus* and *Biomphalaria* intermediate snail hosts were found in 496 sites. After identification and counting, a selection of potential intermediate host snails was examined for parasite infections.

Populations of adult mosquitoes were sampled indoors and outdoors by using light traps in selected houses in 2 villages within 1 km of Koka reservoir and in 2 villages more than 6 km away (the same villages where the larval surveys were conducted). In Tigray, blood samples for malaria (finger prick) were taken in 550 households from 2,780 children below the age of 10 by qualified local health personnel, who also examined the resulting thick and thin blood films. All found positive for malaria were provided with free treatment at the local health centers near Koka and in Tigray.

Data analysis

Villages with and without dams in Burkina Faso were compared using Pearson's Chi-square test. Calculations on the impacts of the projected expansion of small reservoirs in Burkina Faso were based on inventories provided by DGRE and remote sensing data to determine the number of reservoirs at the country scale with their surface and shoreline. Riparian populations within a buffer area of 3 km around each reservoir were then calculated with National Population Census data of 1996 and 2006.

For the analysis of the relationship between malaria case data from the local health centers and distance to the Koka reservoir in Ethiopia, the 13 sampled villages were divided into 4 groups according to distance from the lake and analyzed with the Kruskal–Wallis test. Comparisons of larval and adult mosquito densities between the villages near and far from the reservoir were done using the non-parametric Wilcoxon signed ranks test. Mosquito larval density was calculated as the mean number of *Anopheles* larvae per square meter of water surface. Multiple linear regressions (stepwise) were used in SPSS to investigate relationships between environmental variables and (1) monthly malaria case rates, and (2) *Anopheles* larvae and adult mosquitoes.

Descriptive statistics such as Fisher's exact test were used to determine whether malaria incidence was higher in the intervention sites compared to the control sites in Tigray, while regression analysis was done to identify the factors that were important determinants of malaria infection.

Results and discussion

Increased transmission of schistosomiasis around small reservoirs in Burkina Faso

Analysis of the large data set covering the period 1985 till 2006 showed that transmission of urinary schistosomiasis increased after the construction of small dams. This occurred especially in the semiarid north, where the reservoirs provide perennial water bodies in an area where

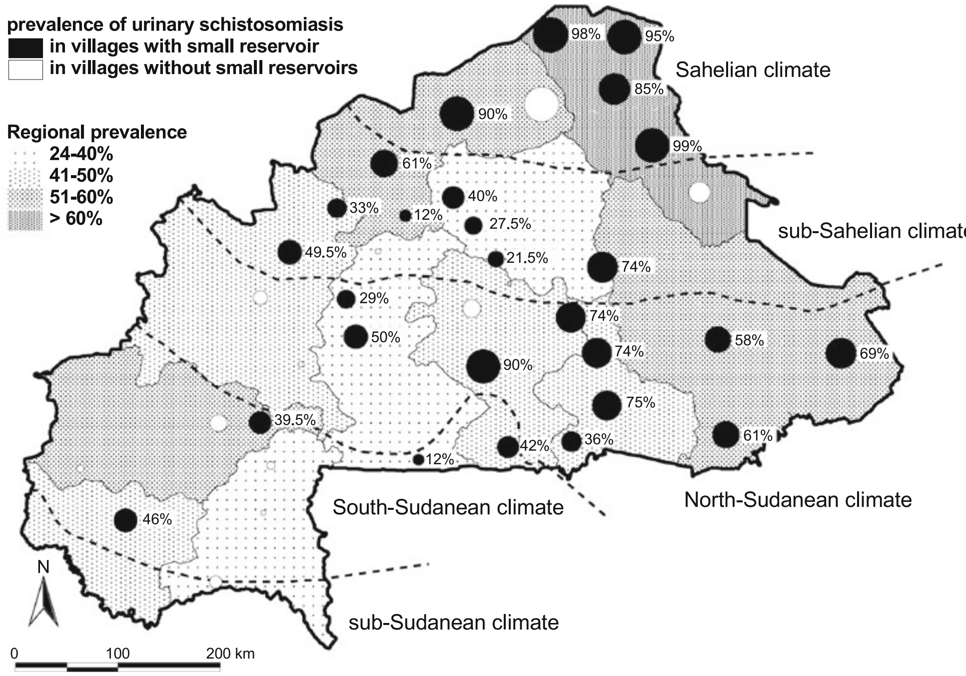

Fig. 2 Mean prevalence of urinary schistosomiasis in 11 regions in Burkina Faso and specific seasonal prevalence in 27 selected villages with and 11 without dams

previously the intermediate snail host depended on temporary pools (Fig. 2). Local variation was high but statistical analyses show a significant (Pearsons $\chi^2 = 0.41$, $P < 0.05$) difference between the prevalence of urinary schistosomiasis in villages with and without dams.

Snail surveys between 1985 and 1995 confirmed the epidemiological findings and showed the importance of small reservoirs in the distribution of intermediate snail hosts of schistosomiasis in Burkina Faso. Most of the intermediate hosts (41% of 496 positive habitats) were found in the small reservoirs, 34% in the rivers, 20% in temporary ponds, 3% in the irrigation canals, and 2% in natural lakes. In the Nakambé Basin, a close relationship was found between snail densities, the presence of small reservoirs, population density, and schistosomiasis transmission. The large number of small reservoirs in the Nakambé Basin offered a wide variety of optimal breeding sites to almost all intermediate snail hosts.

A longitudinal study of *Bulinus* and *Biomphalaria* snails in the southern part of the country suggested that climate change will probably lead to a shift from intestinal to urinary schistosomiasis. *Biomphalaria*, the host of intestinal schistosomiasis, is vulnerable to high temperature, so its distribution in Burkina Faso may be reduced with climate change. At the same time, the host of urinary schistosomiasis, *Bulinus,* was found to be more resistant to long dry periods, so may survive increased weather variability.

The projected expansion of 10,000 small reservoirs (Lemoalle and de Condappa 2009) would enhance the resilience of many small farmers to rainfall variability, but the resulting total shoreline of about 30,000 km would, at least theoretically, put more than 3.5 million people living within 3 km of the reservoirs at an increased risk of water-related diseases such as urinary schistosomiasis.

In Burkina Faso, Ghana, and other countries, transmission of schistosomiasis is closely linked to water resources development (Hunter 2003; Poda et al. 2004a, b; Steinmann et al. 2006). Irrigation systems and small permanent water bodies are preferred breeding sites of the snail hosts as well as principal points of contact between people and the parasite (Poda et al. 2004a; Boelee and Madsen 2006). In recent years, mass school treatments with anti-helminth drugs have reduced transmission, but risks of re-infection, especially with urinary schistosomiasis, are high. This disease is less affected by improved sanitation while climate change probably has limited impacts on its robust intermediate snail host *Bulinus*.

Malaria outbreaks related to water harvesting and storage in Ethiopia

Around the large Koka Dam in the Rift Valley, central Ethiopia, more malaria cases were found in villages closer to the reservoir (Fig. 3). Puddles and cattle hoof prints around the shore of the reservoir, as well as seepage pools downstream of the dam, were found to provide ideal breeding habitat for *Anopheles* mosquitoes. A greater abundance of breeding sites (160 positive out of 298 potential sites, yielding 2,531 *Anopheles* larvae), in combination with high productivity (as indicated by larval density of 3.52), resulted in much greater numbers of adult mosquitoes (mean ratio = 5.77, $P < 0.001$) in those

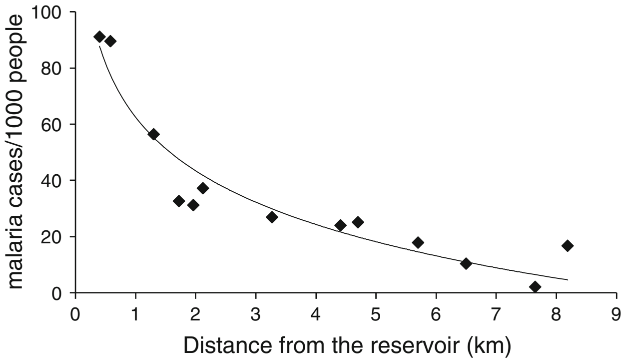

Fig. 3 Average (1995–2007) number of malaria cases in 13 villages at various distances from Koka reservoir

Table 2 Average malaria prevalence (as percentage of "*n*," the number of sampled children under 10 years of age in each group of villages) among 250 households with and without ponds (average of 3 sampling rounds), and 300 households with and without in situ water harvesting in the Tigray Region, Ethiopia, in the period March–May 2005

Type of rainwater harvesting	With		Without	
	n	%	*n*	%
Highland ponds	388	3.6	299	0.7
Midland ponds	464	3	116	0
Lowland ponds	330	35.5	197	6.1
In situ half-moons	954	28.1	36	0

villages located within 1 km of the reservoir than in those located more than 6 km away (46 positive out of 157 potential sites, yielding 539 larvae at mean density of 0.05). Reservoir water level changes were found to be the most significant explanatory variable in multiple regression analysis to describe adult mosquito density in the villages located close to the reservoir ($R^2 = 0.93$, $P < 0.000$ for the village 400 m from the reservoir; $R^2 = 0.70$, $P < 0.000$ for the village at 600 m), while water level changes lagged by 2 months explained part of the variation in monthly malaria case rates in reservoir villages. A moderate correlation ($R^2 = 0.44$, $P = 0.002$) was found between total larval counts in shoreline puddles and falling water levels.

In 5 villages with water harvesting ponds and wells in Tigray, northern Ethiopia, malaria prevalence ranged from 1.1 to 7.7% in the highland villages (both higher than 2,100 m altitude) and from 32.6 to 37.0% in the lowland villages (at average 1,500 altitude), whereas in the 5 control villages, it varied from 0 to 1.4% in highlands and 4.9 to 30.6% in the lowland village. Hence, even in low-land areas, malaria prevalence was higher in villages with ponds than in villages without them (Table 2; $P < 0.001$). The regression results also suggest that better housing conditions and availability of bed nets reduce malaria incidence. In other parts of Tigray, the 2 villages with in situ rainwater harvesting structures at altitudes between 1,700 and 2,100 m had high malaria prevalence (up to 41.7%), especially in households closer to the fields. Households where water harvesting ditches were all more than 500 m away had no positive blood samples at all (Table 2).

For the small water harvesting ponds, the combination of increased breeding sites and higher local air humidity most likely intensified the transmission of malaria in areas where it already was endemic. Most of these ponds have been constructed in lower lying areas throughout Ethiopia, where malaria is common, making the health impacts of these ponds much more difficult to assess. After several informal reports and allegations that these ponds led to epidemics, our study was among the few (Hailu and Merga 2002; Waktola 2008) that tried to quantify the risk and suggest interventions to reduce mosquito breeding in the ponds and increase their overall benefits. However, more detailed studies on a larger number of ponds are necessary to draw solid scientific conclusions, as well as on in situ water harvesting (Yohannes and Haile 2010).

Small reservoirs in Tigray provide year-round *Anopheles* breeding sites, mainly in seepage areas below the dams, leading to much higher case rates near the dams than in villages further away (Ghebreyesus et al. 1999; Yohannes et al. 2005). At these reservoirs, usually located at higher altitudes, the increased malaria transmission was probably due to the combined impact of increased availability of breeding sites and higher local humidity in addition to recent climate change, particularly increased temperature. Together, this led to changes in the life span of *Anopheles* mosquitoes, thus making it possible for the malaria parasite to complete its life cycle even above 2,000 m altitude, where previously this was impossible (Ghebreyesus et al. 1999; Yohannes et al. 2005). This trend may be exacerbated with continued impacts of climate change, increasing the risk of epidemics and eventually year-round transmission of malaria.

Most of the high altitude drier areas of Ethiopia, where rainwater harvesting and water storage facilities have been implemented, are vulnerable to occasional but deadly malaria epidemics. Our findings confirm that increased transmission occurs in association with water storage across scales, ranging from large dams via multipurpose small reservoirs to various types of water harvesting ponds and ditches. This is in line with studies from other countries (Carter et al. 1990; Keiser et al. 2005).

Participatory health impact assessment (PHIA)

Based partly on the findings in Burkina Faso and Ethiopia, a participatory approach to health impact assessment was developed and tested with the following steps:

1. *Screening and scoping*—to determine whether important water-related diseases are prevalent at all in or near the area where the water systems are planned.
2. *Appraisal of health risks*—the actual assessment to identify and examine the best available evidence for quantifying health risks and vulnerable populations, related to a range of potential water interventions under various climate scenarios. The appraisal consists of a combination of participatory and expert techniques, varying from focus group discussions to entomological surveys. Stakeholder consultation helps identify the various users and uses of the future water storage facilities with their own contributions and exposure to risk factors that in turn may all be influenced by climate change.
3. *Formulating and implementing recommendations*—through various rounds of consultations with stakeholders, appropriate and feasible options for prevention and reduction of health risks in water interventions can be developed. By considering a wider range of water storage options, specific health risks could be assessed and the least risky option selected for each location. The formulation of recommendations is not straightforward; the best options are by definition location-specific, which is why involvement of the users and managers of the storage is crucial. Thus, farmers in Southern Morocco intensified vegetation removal from their canals impoundments to reduce snail breeding (Boelee and Laamrani 2004), while in Northern Ethiopia, trees and other vegetation were planted to provide shadow and thus reduce *Anopheles* breeding (Yohannes et al. 2005).
4. *Monitoring and adjusting recommendations*—once the mitigating measures or recommendations have been implemented, monitoring is required to ensure that the recommendations are followed up and to assess what their impact is. This is particularly relevant for proposed changes in water management. Ideally, such monitoring is carried out by local stakeholders.

Health risks and options for mitigation

Based on the local findings from Burkina Faso and Ethiopia and climate change considerations for sub-Saharan Africa (IPCC 2007; Patz et al. 2005, 2007), we endeavored to assess risks of increased transmission of malaria and schistosomiasis associated with various types of rainwater harvesting and water storage (Table 3). The rows in Table 3 show the relative risk as influenced by new construction or expansion of various types of water storage, again as qualitative assessment by the authors. Actual quantitative risk assessment would be a combination of site-specific climate change scenarios and locally feasible options for water storage. Such assessments would greatly benefit from local stakeholder participation, providing information on locally important health risks as well as preventive and mitigating measures.

Intestinal schistosomiasis may increase with floods (increased contamination of surface water with fecal material), while urinary schistosomiasis is expected to increase with droughts as the intermediate snail host tends to be more resistant to a wide range of climate variability, even though its aquatic habitat may get restricted. The multiplication of the parasite in the snail, the cercarial production, may increase with higher temperatures, but quality of the cercariae may deteriorate at a certain cutoff point (Mas-Coma et al. 2009). In any case, higher temperatures will stimulate water contact, thus potentially exposing more people, particularly children, to water infested with snails and schistosomes. This may require more intensive anti-worm treatment campaigns.

For malaria, studies highlighting various aspects of its transmission and their vulnerability to climate change have resulted in different predictions (Gething et al. 2010; Parham and Michael 2010; Thomas et al. 2004). However, in-depth analysis of trends in temperature and mosquito densities showed that the impact of climate change on increased transmission of malaria in East African highlands could not be ruled out (Pascual et al. 2006). For the whole of Africa, an expansion of the transmission season is expected (Tanser et al. 2003).

In the example of Koka dam in Central Ethiopia, densities of mosquito larvae were influenced by the fluctuation of water levels (Kibret et al. 2009) and manipulation of these could be used to disturb breeding of malaria mosquitoes. Such fluctuations would be a promising option for other reservoirs with an extended shoreline in shallow areas, though these may not be prone to mosquito breeding everywhere. For smaller reservoirs and dams without central outlet structure, shoreline management by zoning and adequate coverage (such as vegetation or pebbles) can help reduce vector breeding, at the same time concentrating

Table 3 Relative expected increase in malaria and schistosomiasis transmission influenced by climate change and various types of water storage in sub-Saharan Africa

Influence	Malaria	Schistosomiasis
Reservoirs	xx	xx
Ponds and tanks	xxx	xx
Groundwater		
Soil moisture	x	
Natural wetlands	xx	x

Empty cells means no change is expected, and crosses indicate increased risk (more crosses mean higher risk) water use activities at convenient locations where environmental, biological, or chemical control methods could be applied. For micro-storage, field level structures (in situ water harvesting) may be a healthier choice than household ponds as the fields are usually further from habitation than malaria mosquitoes can fly.

Careful planning, design, and operation of water interventions can thus reduce potential health risks. While the location of dams and ponds is usually determined by technical considerations such as topography, the consequences, for example vector breeding, are completely different in the steep hills of Ethiopia compared to the relatively flat lands of Burkina Faso, where the shoreline will be much longer. However, the water storage facilities themselves can be designed in such a way as to minimize the proliferation of disease vectors and reduce health risks for the users. Various types of water harvesting ponds have been implemented, all with their own advantages and problems, as analyzed by Johnston and McCartney (2010) and by Waktola (2008). Covered tanks have the lowest health risks, but are hard to construct.

Storage in groundwater could be a good alternative to open water storage as it is less associated with water-related diseases such as malaria and schistosomiasis (Table 3). However, technically, this is not possible everywhere, depending on the local geology, soils, and slope, all determinants of the suitability of groundwater storage. Underground water storage may have implications on water quality as recharge, and subsequent pumping of aquifers can lead to mobilization of geological contaminants (arsenic, fluoride), while point pollution (fertilizer, pesticides) is much less visible and more difficult to control than with open water bodies. Climate change may affect the health impacts of groundwater by changing recharge, increasing water temperature, and perhaps even influencing hydro-chemical reactions, all of which may affect contaminant mobilization in ways that are hard to predict, though various models can facilitate forecasting of these risks (e.g., Amini et al. 2008).

Hence, considering a wide range of options is more likely to lead to an optimal and locally acceptable intervention than uncritical application of only one type of water harvesting or storage. Participatory approaches can help to identify user preferences as well as potential impacts and thus enhance future sustainability of the water storage systems (von Korff et al. 2010).

Conclusions

Our findings confirm that water storage, widely promoted for climate change adaptation, can indeed increase health risks, and it is vital that consideration is given to how these adverse impacts can be mitigated. Currently, too little thought is given to the possible public health implications of different options for rainwater harvesting and water storage. In the rush to develop water harvesting and storage for climate change adaptation, care must be taken not to increase the health burden of already vulnerable people. Poorly planned and managed water storage will have adverse implications for public health, which can undermine the sustainability of the interventions. If adverse impacts are to be avoided in future, much greater consideration must be given to the full range of potential health impacts and possible mitigation measures under the altered conditions that will result from climate change.

It is very hard to quantify the impact of climate variability and climate change on disease transmission because of the myriad influences of human factors and other uncertainties. However, it is clear that some adaptation measures, such as increased rainwater harvesting and water storage, may expand the open water surface in susceptible areas with vulnerable populations and lead to increased transmission of water-related diseases. By considering a wider range of options in planning, design, and management of water storage, several health risks could be minimized. PHIA, even if only partially applied, can help to further address these risks in a sustainable way, especially for community-managed water storage. The approach can be further developed to better incorporate climate change issues.

Acknowledgments This paper was prepared as one of the outputs in a project entitled "Rethinking water storage for climate change adaptation in sub-Saharan Africa," funded by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ) as part of its research program on Adaptation of African Agriculture to Climate Change. Earlier studies were funded through a variety of projects and donors, including the CGIAR Challenge Program on Water and Food (CPWF), the Canadian International Development Research Centre (IDRC), the CGIAR Systemwide Initiative on Malaria and Agriculture (SIMA), and the Poverty Reduction and Environmental Management (PREM) Programme of the Netherlands government. We thank our collaborators in the various studies, in particular Abderrahmane Ait Lhaj, Gayathri Jayasinghe, André Koné, Jonathan Lautze, Henry Madsen, Clifford Mutero, and Dramane Zongo. In addition, we thank the reviewers and Pay Drechsel for their constructive comments.

References

Amini M, Abbaspour KC, Berg M, Winkel L, Hug SJ, Hoehn E, Yang H, Johnson CA (2008) Statistical modeling of global geogenic arsenic contamination in groundwater. Environ Sci Technol 42:3669–3675. doi:10.1021/es702859e

Awulachew SB, Merrey DJ, Kamara AB, Van Koppen B, Penning de Vries F, Boelee E, Makombe G (2005) Experiences and opportunities for promoting small-scale/micro irrigation and rainwater harvesting for food security in Ethiopia. IWMI

Working paper 98, International Water Management Institute, Colombo. doi:10.3910/2009.277

Birley MH (1995) The health impact assessment of development projects. HSMO Publications, London

Boelee E, Laamrani H (2004) Environmental control of schistosomiasis through community participation in a Moroccan oasis. Trop Med Int Health 9(9):997–1004. doi:10.1111/j.1365-3156.2004.01301.x

Boelee E, Madsen H (2006) Irrigation and schistosomiasis in Africa: ecological aspects. IWMI research report 99, International Water Management Institute, Colombo. doi:10.3910/2009.099

Boelee E, Cecchi P, Koné A (2009) Health impacts of small reservoirs in Burkina Faso. IWMI working paper 136, International Water Management Institute, Colombo. doi:10.3910/2009.202

Braune E, Xu Y (2010) The role of ground water in sub-Saharan Africa. Ground Water 48:229–238. doi:10.1111/j.1745-6584.2009.00557.x

Carter RC, Brook JM, Jewsbury JM (1990) Assessing the impact of small dams on vector borne disease. Irrig Drain Syst 4(1):1–16. doi:10.1007/BF01145969

Clements ACA, Firth S, Dembelé R, Garba A, Touré S, Sacko M, Landouré A, Bosqué-Oliva E, Barnett AG, Brooker S, Fenwick A (2009) Use of Bayesian geostatistical prediction to estimate local variations in *Schistosoma haematobium* infection in western Africa. Bull World Health Organ 87:921–929. doi:10.2471/BLT.08.058933

Confalonieri U, Menne B, Akhtar R, Ebi KL, Hauengue M, Kovats RS, Revich B, Woodward A (2007) Human health. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 391–431

Erlanger TE, Keiser J, Caldas de Castro M, Bos R, Singer BH, Tanner M, Utzinger J (2005) Effect of water resource development and management on lymphatic filariasis, and estimates of populations at risk. Am J Trop Med Hyg 73(3):523–533. http://www.ajtmh.org/cgi/content/full/73/3/523

Fehr R (1999) Environmental health impact assessment, evaluation of a ten-step model. Epidemiology 10:618–625

Gething PW, Smith DL, Patil AP, Tatem AJ, Snow RW, Hay SI (2010) Climate change and the global malaria recession. Nature 465:342–346. doi:10.1038/nature09098

Ghebreyesus TA, Haile M, Witten KH, Getachew A, Yohannes AM, Yohannes M, Teklehaimanot HD, Lindsay SW, Byass P (1999) Incidence of malaria among children living near dams in Northern Ethiopia: community based incidence survey. Brit Med J 319:663–666. http://www.ncbi.nlm.nih.gov/pubmed/10480820

Hailu M, Merga SN (2002) Workshop on the experiences of water harvesting in the drylands of Ethiopia: principles and practices. December 28–30, 2001, Mekelle. DCG Report 19. Drylands Coordination Group, Noragric, Ås. http://www.drylands-group.org

Hunter JM (2003) Inherited burden of disease: agricultural dams and the persistence of bloody urine (Schistosomiasis hematobium) in the upper East Region of Ghana, 1959–1997. Soc Sci Med 56(2):219–234. doi:10.1016/S0277-9536(02)00021-7

IPCC—Intergovernmental Panel on Climate Change (2007) Climate change 2007: synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change [Core Writing Team: Pachauri RK, Reisinger A (eds)], IPCC, Geneva

Johnston R, McCartney M (2010) Inventory of water storage types in the Blue Nile and Volta river basins. International Water Management Institute, Colombo. doi:10.5337/2010.214

Keiser J, Caldas de Castro M, Maltese MF, Bos R, Tanner M, Singer BH, Utzinger J (2005) Effect of irrigation and large dams on the burden of malaria on a global and regional scale. Am J Trop Med Hyg 72(4):392–406. http://www.ajtmh.org/content/72/4/392.full

Kibret S, McCartney M, Lautze J, Jayasinghe G (2009) Malaria transmission in the vicinity of impounded water: evidence from the Koka Reservoir, Ethiopia. IWMI Research Report 132, International Water Management Institute, Colombo. doi:10.3910/2009.129

L'Hôte Y, Mahé G, Somé B, Triboulet JP (2002) Analysis of a Sahelian rainfall index from 1986 to 2000; the drought continues. Hydrolog Sci J 47:563–572

Lemoalle J, de Condappa D (2009) Water atlas of the Volta Basin-Atlas de l'eau dans le bassin de la Volta. Challenge Program on Water and Food and Institut de Recherche pour le Développement, Colombo, Marseille

Mahé G, Paturel JE, Servat E, Conway D, Dezetter A (2005) Impact of land use change on soil water holding capacity and river modeling of the Nakambé river in Burkina-Faso. J Hydrol 300:33–43. doi:10.1016/j.jhydrol.2004.04.028

Mas-Coma S, Valero MA, Bargues MD (2009) Climate change effects on trematodiases, with emphasis on zoonotic fascioliasis and schistosomiasis. Vet Parasitol 163:264–280. doi:10.1016/j.vetpar.2009.03.024

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. Lancet 367(9513):859–869. doi:10.1016/S0140-6736(06)68079-3

Parham PE, Michael E (2010) Modeling the effects of weather and climate change on malaria transmission. Environ Health Persp 118(5):620–626. doi:10.1289/ehp.0901256

Pascual M, Ahumada JA, Chaves LF, Rodo X, Bouma M (2006) Malaria resurgence in the East African highlands: temperature trends revisited. PNAS 103(15):5829–5834. doi:10.1073/pnas.0508929103

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. Nature 438:310–317. doi:10.1038/nature04188

Patz JA, Gibbs HK, Foley JA, Rogers JV, Smith KR (2007) Climate change and global health: quantifying a growing ethical crisis. EcoHealth 4:397–405. doi:10.1007/s10393-007-0141-1

Poda JN, Sondo B, Parent G (2004a) Influence des hydro-aménagements sur la distribution des bilharzioses et de leurs hôtes intermédiaires au Burkina Faso. Cah études rech francoph/Santé 13(1):49–53. http://www.jle.com/fr/revues/sante_pub/san/e-docs/00/04/03/28/article.phtml

Poda JN, Traore A, Sondo BK (2004b) L'endémie bilharzienne au Burkina Faso. B Soc Pathol Exot 97(1):47–52. http://www.pathexo.fr/documents/articles-bull/T97-1-DK63-6p.pdf

Rockstrom J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resour Res 45. doi:10.1029/2007WR006767

Steinmann P, Keiser J, Bos R, Tanner M, Utzinger J (2006) Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people. Lancet Infect Dis 6:411–425. doi:10.1016/S1473-3099(06)70521-7

Sultan B, Janicot S (2000) Abrupt shift of the ITCZ over West Africa and intra-seasonal variability. Geophys Res Lett 27(20):3353–3356. doi:10.1029/1999GL011285

Tamene L, Park SJ, Dikau R, Vlek PLG (2006) Reservoir siltation in the semi-arid highlands of northern Ethiopia: sediment yield–catchment area relationship and a semi-quantitative approach for predicting sediment yield. Earth Surf Processes 31(11):1364–1383. doi:10.1002/esp.1338

Tanser FC, Sharp B, le Sueur D (2003) Potential effect of climate change on malaria transmission in Africa. Lancet 362(9398):1792–1798. doi:10.1016/S0140-6736(03)14898-2

Thomas CJ, Davies G, Dunn CE (2004) Mixed picture for changes in stable malaria distribution with future climate in Africa. Trends Parasitol 20:216–220. doi:10.1016/j.pt.2004.03.001

Thornton PK, Jones PG, Owiyo T, Kruska RL, Herrero M, Kristjanson P, Notenbaert A, Bekele N, Omolo A (2006) Mapping climate vulnerability and poverty in Africa. http://www.dfid.gov.uk/research/mapping-climate.pdf. Accessed Nov 2010

Thornton PK, Jones PG, Ericksen PJ, Challinor AJ (2011) Agriculture and food systems in sub-Saharan Africa in a 4°C + world. Philos Trans R Soc A 369:117–136. doi:10.1098/rsta.2010.0246

Touré S, Zhang Y, Bosqué-Oliva E, Ky C, Ouedraogo A, Koukounari A, Gabrielli AF, Bertrand S, Webster JP, Fenwick A (2008) Two-year impact of single praziquantel treatment on infection in the national control programme on schistosomiasis in Burkina Faso. Bull World Health Organ 86(10):780–787. doi:10.2471/BLT.07.048694

Vohland K, Boubacar B (2009) A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agr Ecosyst Environ 131(3–4):119–127. doi:10.1016/j.agee.2009.01.010

von Korff Y, d'Aquino P, Daniell KA, Bijlsma R (2010) Designing participation processes for water management and beyond. Ecol Soc 15(3):1. http://www.ecologyandsociety.org/vol15/iss3/art1/

Waktola KD (2008) Malaria and pond-based rainwater harvesting linkages in the fringes of central highland Ethiopia. Rural and remote health 8(3):956. http://www.rrh.org.au

WHO (2008) The global burden of disease, 2004 update. World Health Organization, Geneva

WHO (2010) World malaria report 2010. World Health Organization, Geneva

Wisser D, Frolking S, Douglas EM, Fekete BM, Schumann AH, Vörösmarty CJ (2010) The significance of local water resources captured in small reservoirs for crop production—a global scale analysis. J Hydrol 384:264–275. doi:10.1016/j.jhydrol.2009.07.032

Yohannes M, Haile M (2010) The potential of in situ rain water harvesting for water resources conservation on malaria transmission in Tigray, Northern Ethiopia. MEJS 2(2):49–63. http://www.ajol.info/index.php/mejs/article/view/57675

Yohannes M, Haile M, Ghebreyesus TA, Witten KH, Getachew A, Byass P, Lindsay SW (2005) Can source reduction of mosquito larval habitat reduce malaria transmission in Tigray, Ethiopia? Trop Med Int Health 10(12):1274–1285. doi:10.1111/j.1365-3156.2005.01512.x