

The role of small scale sand dams in securing water supply under climate change in Ethiopia

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Abstract Community-based water storage in semi arid areas can help to adapt to climate change and mitigate household water shortages. Since little is known on the downstream effects of local water storage, this study employs a water balance model to perform a catchment scale assessment of upscaling local scale water storage in sand dams. The impacts of increasing water storage is evaluated under current climate conditions and future climate change scenarios. Survey information is used to estimate current and future water demand and assess the benefits derived from current sand dams in the Ethiopian study area. Using an indicator of the environmental flow concept, downstream hydrological impacts are simulated for different scenarios. Storage by 613 dams, supplying water to 555,000 people, has no impact on environmental flow downstream of the sand dams. Storage by 2190 dams leads to a modest increase in the number of months with low flow (4 to 9 %). Projected climate change leads to a larger increase in the number of low flow months of 0 to 29 %. Joint climate change and maximum storage scenarios cause an increase in low flow months from 4 to 50 %. Under the most extreme climate change projection 4.5 % of the wet season discharge is stored in sand dams. Because of the local benefits of improved water supply and the acceptable range of downstream impacts, sand dams appear to be a viable way for supplying drinking water in this catchment as well as in other semi-arid regions with similar conditions.

Keywords Water harvesting · Adaptation · Climate change · Catchment model · Environmental flow · Storage · Sand dam

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1 Introduction

Projections of climate change in semi-arid regions, such as Ethiopia, show that temperatures will rise, and droughts will occur more frequently (Rockstrom et al. 2007). Precipitation will become more intense, and will occur during shorter periods (IPCC 2012). Year-to-year rainfall records in Ethiopia show that rainfall is seasonal and already highly erratic, hampering the socio-economic development of these areas. Since 95 % of the agricultural area in Ethiopia relies on rain-fed farming systems (Dixon et al. 2003; World Bank 2006), climate changes may have a negative impact on the productivity of major crops (e.g. Knox et al. 2012). Hayashi et al. (2012) and Rockstrom et al. (2009) show, accounting for both socio-economic and climatic changes, that the population subject to water stressed conditions will increase up to 36 % towards 2050. In addition, achieving Millennium Development Goal 7, which aims to provide world wide access to clean drinking water for all communities, will be more challenging because of these future changes (World Bank 2010).

One way to cope with the negative impacts of climate change is to increase the water storage capacity, to bridge the dry periods (Hayashi et al. 2012; World Bank 2010; IWMI 2009; IPCC 2007a). The construction of large-scale water infrastructures in rural areas is often not realistic due to lack of financing, shortage of knowledge, lack of infrastructure, and lack of adequate institutions to govern such developments (Baguma and Loiskandl 2010; van der Zaag and Gupta 2008; WHO 2007). Local scale water harvesting techniques are often mentioned as feasible measures to improve water security in rural areas with low population densities. These techniques capture precipitation or run-off during the short periods of precipitation and store the water for later use. Hence helping the users to cope with intra-annual variation in water availability, which are expected to increase due to climate change (IPCC 2012). Sand dams, a specific class of subsurface dams, are an example of such techniques (e.g. Lasage et al. 2008). They have been proven to be relatively cheap and effective to local communities in supplying water, for instance, in East Africa and India (e.g. Lasage et al. 2008; Tuinhof et al. 2012). Sand dams are constructed partly above ground and partly below ground in seasonal rivers, mostly as a concrete or masonry structure, varying between 10 and 100 m in width to 4–6 m in height. Sand and soil particles transported during periods of high flow are allowed to deposit behind the dam (hence the name ‘sand dam’). When the space behind the dam is filled with sand, water can be stored within the sand thereby limiting losses from evaporation (Hellwig 1973a, b). The sand also serves as a filter for improving water quality, and because the water is stored sub surface it does not serve as breeding grounds for mosquitoes (Culicidae) (Lasage et al. 2008). Water becomes available by pumping the water from the artificial sand aquifer that is created behind the dam.

Some field scale studies on sand dams exist focussing on design of dams (Forzierie et al. 2008), the hydrological processes and fluxes around sand dams (Hut et al. 2008; Quilis et al. 2009; Van Loon et al. 2011). Other studies have qualitatively assessed the impacts of sand dams on a catchment scale (Ertsen and Hut 2009; Aerts et al. 2007; Nissen-Peterson 2006). Recent research shows sand dams can be effective to secure water for local communities in dry periods (Aerts et al. 2007; Lasage et al. 2008), large-scale implementation of sand dams is being considered in Ethiopia (MoWR 2011; Tuinhof et al. 2012). Such upscaling, however, requires an evaluation at the catchment scale to assess the impacts of sand dams to downstream hydrological conditions and whether they are still effective assuming climate change (Falkenmark et al. 2001; Rockstrom et al. 2010; Bouma et al. 2011). Several assessments of the effect of small reservoirs in (semi-) arid environments on water availability and downstream discharge show a range of outcomes. Large reductions in downstream discharges of 64 %, 50 %, 32 % and 18 %, through upscaling upstream small scale

water harvesting, are found by Schreider et al. (2002), Garg et al. (2012), de Fraiture (2007), and Wisser et al. (2010), respectively. Bouma et al. (2011) found a reduced downstream flow of 11 %, because of increasing upstream water harvesting. The additional water was used for increasing upstream agricultural land and led to a reduction in downstream agricultural production. The annual benefits, however, of this change in up-, and downstream agricultural production was close to zero. In addition, some studies on Ethiopia and other sub-Saharan countries at the sub-catchment level (1 to 100 km²) draw qualitative conclusions on the impact of implementation of upstream storage measures. They conclude that upstream storage can also lead to a more balanced downstream water availability and cause only a minor reduction in total yearly downstream discharge (e.g. Balana et al. 2012; Nyssen et al. 2010; Alemayehu et al. 2009; Pachpute et al. 2009; Ngigi et al. 2008).

These varying results in downstream impacts from local water storage shows there is a lack of quantitative research, which combines local scale hydrological measurements around sand dams and community water use from sand dams with an impact analysis at the catchment scale of the upscaling of these measures. This is, however, key to understanding the possibilities for upscaling these small scale measures (e.g. Glendenning et al. 2012; Rockstrom et al. 2002).

The goal of this paper, therefore, is to evaluate the downstream effects of catchment wide upscaling of sand dams, under conditions of climate change in Ethiopia. The study combines a survey to evaluate the use of these dams by the local population, and a model-based assessment of the downstream hydrological impacts under current and future climate conditions. For this, we have defined the following objectives:

- Develop and parameterize a hydrological model to assess the downstream hydrological impacts of upscaling sand dams in a catchment.
- Downscale future climate change scenarios which can be used as input to the hydrological model to assess changes in water availability.
- Perform a local scale household survey in sand dam communities to capture current water use and water demand, and to develop future water demand strategies based on both household surveys and statistical population trends. Additional hydrological measurements around sand dams will provide data on water availability to users.
- Simulate the downstream water availability using projections on both climate change and future water demand. Water demand is reflected through the upscaling of sand dams to meet the demand. Hydrological indicators are used to evaluate the downstream impacts under both current and future climatic conditions.

The study is conducted in the Dawa catchment, which covers most of the Borana zone, in the southern part of Ethiopia. This area is representative of the conditions of a large region in Eastern Africa.

2 Data and methods

2.1 Overview

Figure 1 provides an overview of the methodology applied to the Dawa catchment in Ethiopia. Using a range of different input data, we calibrated and validated a model to simulate changes in water balance and to estimate the downstream impacts of different water storage strategies for: (a) the current climatic situation; and (b) three climate change scenarios for 2050 based on two

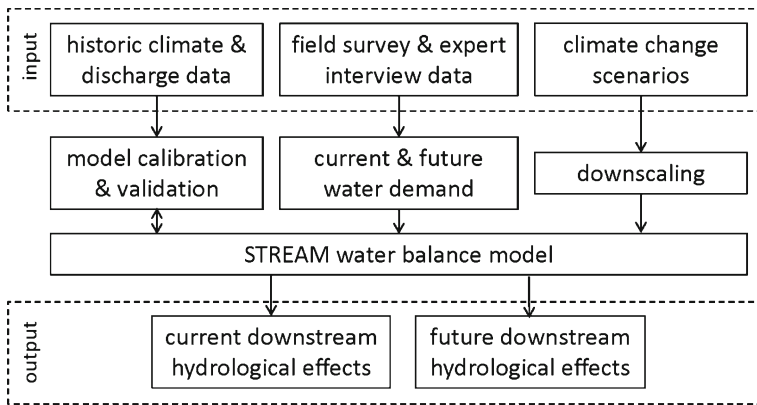


Fig. 1 Overview of analytical methods used to study the Dawa, Ethiopia catchment

different GCMs (Global Circulation Models). These analyses focus on long term changes. A field survey was conducted to both determine the current and future water demand. The current use of water stored by dams by the local population in the study area is evaluated to establish their effect on water security of the households.

Historic discharge is used to calibrate and validate the STREAM (Spatial Tools for River basins and Environment and Analysis of Management options) model (Section 2.4). Historical information on precipitation and temperature is used for downscaling GCM data (Section 2.5) as input to the water balance model. Furthermore, the storage capacity of a sand dam was established by detailed monitoring at a sand dam site, and additional information on general characteristics was obtained from several other sites in the Dawa catchment. Current and future water demand is derived from a household survey and from information on population size and population growth in the region. This information is used to develop two sand dam storage strategies (Section 2.6). Future changes in downstream water availability are the result of the combination of water storage strategies and climate change scenarios. The frequency of occurrence of not reaching the minimal monthly environmental flow at Melka Guba station during the rainy seasons is used as an indicator of downstream impacts. The second indicator for downstream impacts is the percentage of wet-season discharge that is stored by the dams. The following sections discuss the different parts of the methodology in more detail.

2.2 Study area

The Dawa catchment area lies in the Borana and Guji zones, in the southern part of Ethiopia. The river joins the Genale river at Juba ($4^{\circ}17'N$ $42^{\circ}08'S$) (Fig. 2). Its altitude ranges between 500 and 2,500 m, and the catchment area covers about 56,000 km², of which 70 % are lowlands. The lowlands are characterised predominantly by a semi-arid Savannah landscape. The yearly average precipitation is 873 mm for the period 1975 to 2000, and is highly variable (Fig. 3a). Precipitation is related to altitude, higher areas receive more rain than the low lands. There are two rainy seasons: from March to May, and from September to November. These alternate with two dry seasons from June to August, and from December to February, which, respectively, are considered to be the short and the long dry seasons (Riché et al. 2009). Once every 4 to 5 years a drought occurs (Amsalu and Adem 2009). Monthly average temperature varies between 17.5 °C and 21.5 °C over the course of year (Fig. 3c).

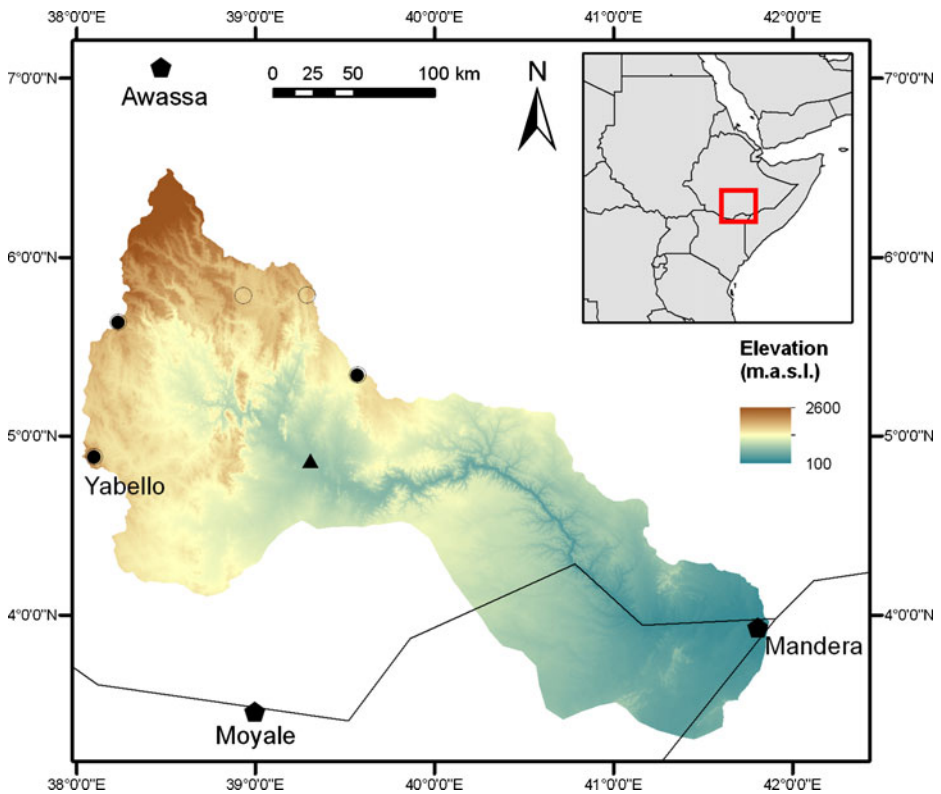


Fig. 2 Location of the Dawa basin in Ethiopia. *Open circles* indicate precipitation stations; *filled circles* are combined precipitation and temperature stations. The *triangle* represents the gauging station in the Dawa river at Melka Guba

Most of the people living in the Dawa catchment area are dependent on livestock farming and small scale farming and live in the rural area (Lasage et al. 2010; Angassa and Oba 2008; Census 2008;). 80 % of the inhabitants are considered to be poor (Tache and Oba 2010). Several larger villages of 10,000 to 30,000 people are located in the upstream part of the Dawa catchment. The rest of the population lives in small settlements spread around the countryside. Far downstream, where the Dawa river joins the Genale and Gestro rivers to form the Jubba river, is the town of Mandera, which has 53,000 inhabitants (KNBS 2009).

During the dry season, women and children spend the better part of their days collecting drinking water, as clean water availability is limited according to local government institutes like the Borana Zone Disaster Prevention and Preparedness Desk (BZDPPD 2003; Borona Zone Water Resources Office 2009). The recent decades boreholes up to 100 m deep have been installed by the government and NGOs (Non Governmental Organisations) to improve peoples' access to drinking water. However, over large areas the groundwater potential is low (Cossins and Upton 1988). In some parts groundwater is present at 30 m below the land surface. Due to the low water availability, low agricultural production, lack of infrastructure, and poverty in general, malnutrition is widespread in Borana (BZDPPD 2003). Since the 1980s the average population growth rate was 2.75 %, caused by natural growth and net immigration (Census 2008; Homann et al. 2008).

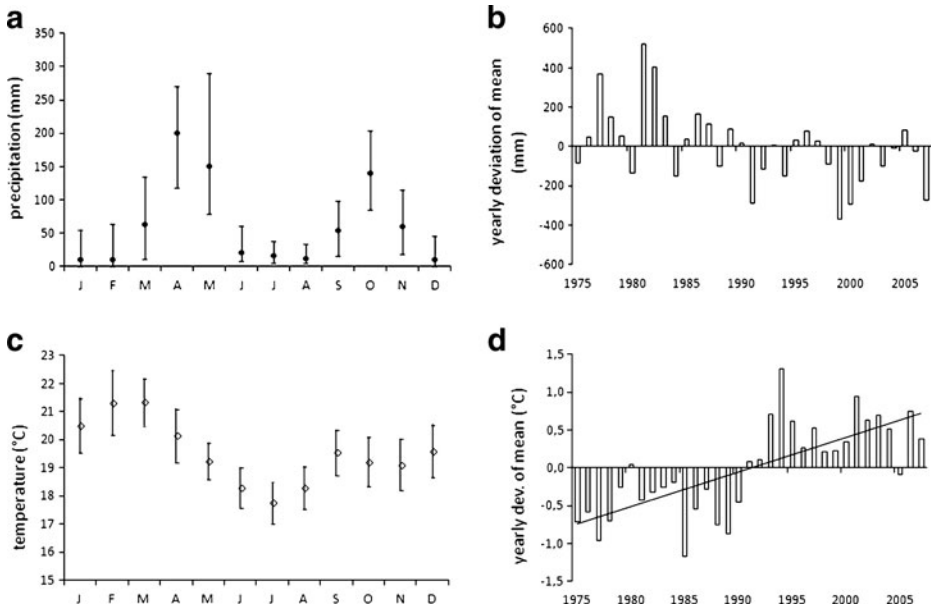


Fig. 3 **a** Median monthly precipitation in the Dawa catchment and the 10 and 90 percentiles; **b** Yearly deviation from long-term average precipitation; **c** Average temperature with the standard deviation in the Dawa catchment; **d** Yearly deviation from the long term average temperature (significant at $p < 0.01$). Source: Precipitation is based on data from five weather stations of the Ethiopian National Meteorological Agency and temperature on three stations, both for the period 1975–2007

2.3 Historic climate data

Historical data on daily precipitation and temperature for five weather stations in the Dawa catchment district have been derived from the Ethiopian National Meteorological Agency for the period 1975–2007. Analysis of the meteorological data shows that precipitation is highly variable (Fig. 3a and b). The seasonal variation in precipitation is shown in Fig. 3a. Within a year periods with hardly any precipitation and periods with fair amounts of precipitation alternate. The wet season months show large variation in the amounts of precipitation between years, indicated by the 10 and 90 percentiles. This is also visible in Fig. 3b, which shows the inter annual variation in precipitation. Trends in annual and seasonal rainfall in the Genale-Dawa basin have been analysed by Cheung et al. (2008). They do not notice significant changes in annual rainfall between 1960 and 2002. However, a study on seasonal trends in rainfall by Verdin et al. (2005) shows that rainfall from February to May have been decreasing consistently since 1990s. Temperature shows a smaller variability per month (Fig. 3c), and the data on the average yearly temperature shows a rising trend (significant at $p < 0.01$) (Fig. 3d).

2.4 Setting up hydrological model STREAM

The STREAM model is a grid based water balance model that calculates run-off on the basis of precipitation and temperature data and several land surface characteristics (van Deursen and Kwadijk 1994; Aerts et al. 1999). The STREAM model has been used in numerous studies on hydrology and climate change, including in semi-arid areas (Aerts et al. 2006,

2007; Bouwer et al. 2006). The STREAM model for the Dawa river basin was developed at a spatial resolution of $185 \times 185 \text{ m}^2$. Calculations are made for monthly time steps. For each cell the water balance is calculated using a direct run-off, soil water and groundwater component, based on a number of parameters (Aerts et al. 1999). Studies by Middelkoop et al. (2001), Winsemius et al. (2006) and Aerts et al. (2007) confirm that a monthly time step is sufficient for detecting decadal, inter-annual, and seasonal changes in the hydrological cycle, such as those caused by water consumption and climate change.

The water balance is calculated for each grid-cell using a direct run-off, soil water, and groundwater component, according to a number of parameters (Aerts et al. 1999). Total run-off T is calculated as:

$$T = R + M + B \quad (1)$$

where R is direct run-off, M is snow melt, and B is the base flow origination from groundwater, all in mm per month.

The direct run-off R is calculated from the soil water balance S , using a separation coefficient S_c :

$$R = S \cdot S_c \quad (2)$$

The remaining amount of water from the soil water balance is redirected to the groundwater (TG), using

$$TG = S - R \quad (3)$$

The base flow is calculated from the amount of groundwater GW stored using a recession coefficient r_c :

$$B = GW / r_c \quad (4)$$

The soil water balance and actual evaporation are calculated for each month using the equations from Thornthwaite and Mather (1957). Actual evaporation is estimated from adjusted reference evaporation, using a crop factor k_c and a reduction coefficient F_{red} that acts as calibration factor:

$$ET_0' = ET_0 \cdot K_c \cdot F_{red} \quad (5)$$

Reference evaporation is calculated from temperature, using the formulas from Thornthwaite (1948). FAO (Food and Agriculture Organization) factors were used for adjusting the reference evaporation to different land-cover types using crop factors (Doorenbos and Pruitt 1975). Land-cover classes were taken from the Global Land Cover Characteristics database Version 1.2, produced by the International Geosphere Biosphere Programme (IGBP). Parameters for the maximum soil water holding capacity were taken from a global data set compiled by the United States Department of Agriculture (available from <http://www.nrcs.usda.gov/>) with a resolution of 2 arc minutes (about $3.5 \times 3.5 \text{ km}$). The model script that provides insight into the processing of these parameters is presented in the supplementary materials A. The digital elevation model was derived from the SRTM (the Shuttle Radar Topography Mission) data set ($90 \times 90 \text{ m}$, <http://srtm.usgs.gov/>) and has been re-sampled to a resolution of $185 \times 185 \text{ m}$. The digital elevation model is used for stream flow routing.

The STREAM model was set up to cover the Dawa catchment down to the town of Melka Guba, as discharge data was not available for stations further downstream. This covers the

upper part of the catchment that is most suitable for sand dam constructions in wadis and sandy ephemeral rivers. The model was calibrated using downscaled HadCM3 (Hadley Centre Coupled Model, version 3) and ECHAM5 (European Centre for Medium-Range Weather Forecasts Hamburg Model, version 5) data for mean monthly discharge values over the period 1972–1976 and 1987–1999. The model validation was done using data for the period 2001–2006. These periods were chosen, since mean observed discharge data was available from the Ethiopian National Meteorological Agency for this period. The calibration of the model involved the adjustment of a reduction factor that affects the reference evaporation (see Eq. 5); a coefficient that determines the separation between groundwater recharge and run-off (Eq. 2); and a recession coefficient that determines the delay of the groundwater flow (Eq. 4) (Aerts et al. 1999). The calibration involved the match to observed total annual run-off, as well as to seasonal patterns using the efficiency coefficient from Nash and Sutcliffe (1970), which explains the proportion of observed monthly discharge explained by the model. It compares the mean square error generated by a model simulation with the variance of the target output sequence (Schaeffli and Gupta 2007). Table 1 shows the calibration and validation results and Supplementary material B shows a graph of the results. The Nash and Sutcliffe coefficients of the model runs are between 0.56 and 0.87, indicating an acceptable level of performance of the model for all runs (Moriassi et al. 2007). The T-test further shows that for all runs, except the Hadley validation run, the simulated data do not differ significantly from the measured data.

2.5 Downscaling climate change scenarios

Climate change projections on monthly temperature and precipitation for the coming century have been obtained from HadCM3,^{1 2} and ECHAM5² GCM simulations (IPCC 2007b). These models are forced by greenhouse gas (GHG) scenarios, which describe different projected concentrations of greenhouse gas for the next 100 years. The two models were selected based on a performance assessment described by Cai et al. (2009). For this study, we used the results from HadCM3 and ECHAM5 projections forced with the A1b, A2 and B1 greenhouse gas scenarios (IPCC SRES 2000), for the period 2000–2100. These scenarios originate from the United Nations Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (e.g. Solomon et al. 2007), and cover the upper (A1b and A2) and lower (B1) boundaries of the greenhouse gas concentrations in the atmosphere in the 21st century. For downscaling purposes, the historic emission scenario 20C3M was used for the period 1950–2000, which prescribes greenhouse gas and aerosols on an annual basis based on observed values during the 20th century (IPCC 2000). The HadCM3 data are available on a $2.5^{\circ} \times 3.75^{\circ}$ grid ($\sim 200 \times 250$ km). In order to use the HadCM3 and ECHAM5 data for the Dawa case-study area, the data need to be downscaled to the appropriate spatial resolution (Choi et al. 2009; Diaz-Nieto and Wilby 2005). Two basic downscaling steps are needed, following McGuffie and Henderson-Sellers (1997) and Aerts et al. (2007). The first step is the spatial downscaling of the coarse GCM data to the model resolution of

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² We acknowledge the international modelling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organising the model data analysis activity, and the IPCC WG1 TSU for technical support. This work, including access to the data and technical assistance, is provided by the Model and Data Group (M&D) at the Max-Planck-Institute for Meteorology, with funding from the Federal Ministry for Education and Research and by the German Climate Computing Centre (DKRZ).

Table 1 Results of statistical tests for calibration and validation

Model	Nash-Sutcliffe model efficiency	T-test	% [#]
HadCM3 Calibration	0.87**	0.74*	100
HadCM3 Validation	0.56**	0.001	175
ECHAM5 Calibration	0.78**	0.82*	101
ECHAM5 Validation	0.87**	0.78*	93

[#] % indicates the annual mean simulated discharge as a percentage of the observed annual discharge

*Indicates no significant difference between the mean of observed and simulated data

**The Nash and Sutcliffe coefficient indicates an acceptable level of performance of the model

185×185 m, using standard GIS interpolation techniques (Bouwer et al. 2004). The second step (statistical downscaling) is to transform the GCM output in such a way that the main statistical properties of historically observed data (two periods between 1972 and 1999) match those of the transformed climate model output for the same period. The formula (Eq. 6) used for statistical downscaling corrects GCM data not only for the average observed climate but also for the observed variance (Bouwer et al. 2004). The formula is constructed in such a way that both the average climate and the variability of simulated series after correction match the observation.

$$a'_{gcm,i} = \left(\frac{a_{gcm,i} - \bar{a}_{gcm,i}}{\sigma_{gcm,i}} \right) * \sigma_{obs,i} + \bar{a}_{obs,i} \quad (6)$$

Where:

- $a'_{gcm,i}$ is the corrected climate parameter (total precipitation or average temperature) in month i ;
- $a_{gcm,i}$ is the simulated climate parameter in month i ;
- $\bar{a}_{gcm,i}$ is the average simulated climate parameter in month i ;
- $\sigma_{gcm,i}$ is the standard deviation of the simulated climate parameter in month i ;
- $\sigma_{obs,i}$ is the standard deviation of the observed climate parameter in month i ; and
- $\bar{a}_{obs,i}$ is the average observed climate parameter in month i .

A drawback in the approach is that the time series of observed climate data are relative short (18 years in total). The standard deviation of the climate parameters over this period could be affected by an extreme event. In the case an extreme event occurred in the observed period, the standard deviation of the observed period would be an overestimation, leading to an overestimation in the simulated dataset. The downscaled GCM data has the same accuracy as the original GCM data. By using multiple models and multiple scenarios a range of possible future climatic circumstances was included in this study. By including these different future circumstances, the outputs of the study are more robust.

The downscaled temperature and precipitation projections for both HadCM3 and ECHAM5 for the different GHG scenarios show comparable results (also see Supplementary material C and D). The projections show on average an increase in future precipitation: in particular the 95th percentile increases from 1,317 mm to 1,582 mm per year, and the median increases from 931 mm to 1,046 mm. Temperature is projected to change significantly in the Dawa catchment. Towards the end of the 21st century it is projected to rise by roughly 3 °C under the B2 scenario and by about 4 °C under the A1b and A2 scenarios.

2.6 Developing water storage and demand strategies

According to a literature review of water harvesting techniques by Lasage and Verburg (*in press*), sand dams contain on average approximately 1,000 m³ extractable water. On this basis, two storage strategies were developed to meet current and future water demand by storing water in sand dams. These storage strategies are used to assess how many dams are needed to meet the demand, and to assess the downstream impacts of such strategies.

To estimate water demand for the current and future situation, and to gain insight in household water security in the wet and dry seasons, a field survey was carried out in 2010. Data on household water availability and water use in the Dawa catchment was collected. The survey data was also used to analyse differences in water use between households with access to water from a sand dam and households without access to water from a sand dam. In total, 316 households were interviewed using a questionnaire, of which 37 had access to water from a sand dam. The number of households with access to water from a sand dam is low, because only a few sand dams have been constructed in the area. In addition, the survey also aimed to collect information on the effect of sand dams on household livelihood. The data of the field survey contains information per household for: water use in the dry and wet season; available water sources other than sand dams (including distance, and period of use); daily activities of the household members (separate for women, men, and children); household empowerment (ability to access government institutes and NGOs, involvement in community institutions); sensitivity to droughts (impact of the dry year of 2000 on the household); livestock and agriculture; water demand; and other general information concerning the household composition and activities. In the same period, several meetings and interviews were held with experts in the region, working at government offices, NGOs, universities and the private sector, in order to validate the results of the survey, and to acquire additional information.

For the calculation of current water demand, we use population data from the Census (2008), which records that 615,000 people live in the districts included in the model of the Dawa catchment. 555,000 of these people live in the rural areas. One household consists, on average, of 5.8 people. From the survey, we derive the average dry-season household water demand, covering the months December to February and June to August (Fig. 3a). During this period additional water can be supplied by sand dams when other sources run dry. For future water demand, we assume population growth continues at 2.75 % following historic growth rates from the past few decades (Census 2008; Homann et al. 2008). This leads to a population of 1,556,000 people in 2050. The survey data shows that dry month weekly water use, which covers drinking, cooking and washing, increases from 498 to 635 l when households get access to additional water from sand dams (Fig. 6). We therefore assume that water use will increase towards 2050 because more water is available due to the construction of sand dams. This leads to a total dry season water demand of 612,687 m³ for the current situation, and 2,190,246 m³ for the situation in 2050 (Table 2).

Sand dams are located upstream, in the capillary streams of the Dawa catchment, where run-off occurs as flash floods after intense precipitation. On the basis of interviews with sand dam users and experts, and our own observations, it was assumed that that storage takes place during the wet season, and that every month one-third of the stored water leaves the reservoir. This assumption is supported by the data from gauges in the field (supplementary material E shows daily precipitation and the water levels behind a sand dam). If discharge is too low during a wet-season month, there will be no replenishment of the reservoir. This recharge demand is then added to the following month, as water use will continue. The effective storage capacity takes into account the amount of water that is available for use. A

Table 2 Details of the water demand scenarios

	Current	2050
Population	555,000 people	1,556,000 people
HH water use per week	498 l	635 l
Total water demand	612,687 m ³	2,190,246 m ³
Dams required to meet demand	613 dams	2190 dams
Climate scenarios	20C3M	A1B, A2, B2

dam loses water because of evaporation (5 %), seepage (5 %), and retention of water to the soil (7 %) (Lasage and Verburg *in press*). Thus, the total storage capacity for a dam that supplies 1,000 m³ of extractable water is 1,170 m³ when accounting for these losses. Accounting for the water demand, 613 and 2,190 dams are needed to meet respectively the current and future water demand (Table 2). These strategies will be referred to as the ‘moderate strategy’ and the ‘high strategy’ in the remainder of this paper.

2.7 Indicators for assessing downstream effects

Downstream impacts of upstream water storage scenarios are assessed using the concept of environmental flow described by Smakhtin and Weragala (2005). Environmental flow represents a degree of variation in discharge that is assumed to be necessary to support different natural processes and downstream uses (Smakhtin and Weragala 2005). It is defined as one standard deviation above and below the average discharge. As this case study is located in a semi-arid region, the minimal flow is especially important and the maximum flow is less relevant (mean monthly discharge – 1SD \geq modelled monthly discharge). The discharge data set is not normally distributed, so we calculate the minimal flow by taking the 16th percentile of historic discharge for the wet season months April to June, and September to November.

We determine whether the modelled discharge falls below this environmental flow criterion more frequently after the construction of more sand dams as compared with the historic situation. A similar analysis is made for the climate change scenarios, where discharge may reduce over the longer term. As low flows are common to the river regime in the catchment, the occurrence of low flows is only a partial indicator of the impacts on the downstream hydrology. A second indicator for assessing the downstream impacts of upstream water storage and water use is the percentage of wet-season discharge that is stored by the dams.

3 Results

3.1 Sensitivity, climate change, and downstream discharge

Discharge is defined as the discharge of the Dawa river at Melka Guba simulated by STREAM, calibrated using either the Hadley model (HadCM3 20C3M data) or the Echem model (ECHAM5 20C3M data). Table 3 shows how low and high discharge is affected by varying the values of four parameters of the STREAM model, for the period 1961–1990. Lower values for WaterH, CropF and ToGW result in fewer months with low run-off and

Table 3 Sensitivity analysis of parameters STREAM model

Parameter	Low - high value	Total average yearly discharge (m ³ /s)	Percentage of months flow occurs (m ³ /s)	
			<25	>300
WaterH	0.5–1.5	2908–2219	4.7–10.6	22.8–15.3
CropF	0.5–1.5	4138–1445	0.0–21.9	45.0–10.3
ToGW	0.2–0.6	2454–2452	4.4–12.2	19.4–17.8
C	1.0–3.0	2453–2450	8.0–0.0	18.0–15.3

more months with high run-off modelled for Melka Guba station. For parameter *C*, the relation is the other way around, a low value results in more months with low run-off and less months with high run-off. Total yearly run-off is not affected by *ToGW* and *C*, while *WaterH* and *CropF* change the modelled total yearly discharge. The model is especially sensitive to variation in the *CropF* parameter. Higher temperatures projected for climate change are used in the *CropF* parameter, and are thus expected to reduce the modelled run-off for the climate change scenarios.

The simulation results show that discharge reduces under all climate change scenarios, for both GCMs (Fig. 4a and b). Scenarios A1B and A2 result in a strong reduction in discharge, especially during the first rainy season. Average annual run-off decreases from the current 343 m³ to 183–330 m³ in 2050, where it should be noted there is quite some variety in simulation results using different GHG scenarios and the GCMs.

The effect of climate change and the two water storage strategies (Section 2.6) on discharge is summarised in Tables 4 to 6. Table 4 shows the impact of constructing sand dams on discharge, using monthly historic discharge data (1972–1976 and 1987–2006) and calculating the effect of storage by sand dams in EXCEL spreadsheet software, in order to gain insight into the impacts of storage for current climatic circumstances. The table shows the percentage of months over the studied period, where discharge falls below the 16th percentile environmental flow requirement, as compared with the situation without dams. If currently, 613 sand dams of the moderate strategy were to be present in the catchment, there would be no change in low flow occurrence. For the high strategy, however, the April and September low flow occurrence would rise from 18.2 % to respectively 22.7 % and 27.3 % of these months for the studied period. This means that in 22.7 % of the years the April flow is below the environmental flow requirement.

Tables 5 and 6 show the percentage of months (i.e. all of the Aprils, Mays, etc.) where discharge is below the environmental flow requirement at Melka Guba, for the period 2036–2065. The figures in these tables are based on using both basic HadCM3 and ECHAM5 simulations, as well as the two storage strategies. This period of analysis was chosen as it takes time to construct such large numbers of sand dams, while also accounting for the lifetime of the dams of 40 to 50 years (Lasage and Verburg *in press*). Compared with the current climatic conditions (Table 4), all simulations using climate change scenarios show an increase in low flow occurrence (Tables 5 and 6). These tables do not show a clear change in timing of the rainy season, almost all runs show a reduction in available water. When comparing the two storage strategies, our results show that for the moderate strategy the discharge in April and November will fall below environmental flow requirement more frequently for all three climate change scenarios (Table 5). September and October show an increase in low flow occurrence for two of the three climate scenarios. For May and June, there is no change in the occurrence of low flow

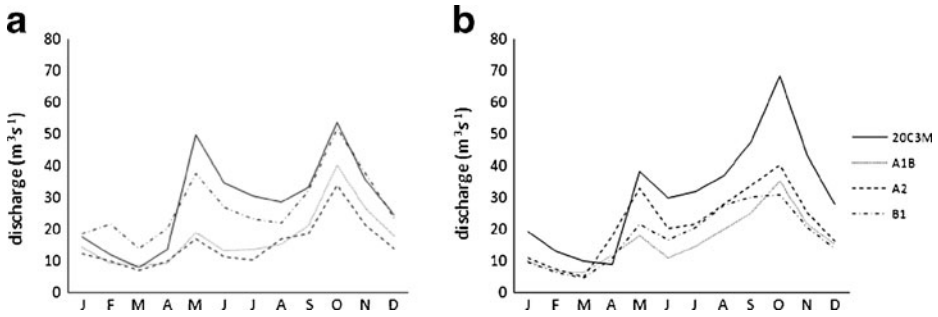


Fig. 4 Modelled mean monthly discharges for 2050 using three GHG scenarios for **a** the STREAM model calibrated on ECHAM5 data; **b** the STREAM model calibrated on HadCM3 data

events. The combination of the high strategy and the Hadley climate scenarios result in an increase in low flow occurrence of 0 to 17 % points. The difference in low flow occurrence between the moderate and the high strategy is relatively small, ranging from 0 to 10 percentage points. However, the available water in the areas benefitting from the dams increases by a factor of 3.5 as the number of dams increases from 613 to 2,190.

In Table 6, the effect of the two storage strategies is evaluated using the Echam model and climate data. The results for the moderate strategy show no change in the percentage of months where discharge falls below the minimal environmental flow requirement. For the high strategy, 2 months show no change; 2 months show an increase in low flow occurrence for one scenario; and April and October show a higher percentage of months where discharge falls below the environmental flow for two scenarios. The largest impact is at the start of the rainy season, when the dams are empty, and the discharge is relatively low compared to the discharge of the other months of the rainy season (Fig. 4).

Table 7 shows the reduction of discharge as result of dam construction as a percentage of the discharge per rainy season, using the climate data of the Hadley A1b scenario. This model and scenario have the highest impact on low flow (see Table 5). On average, between 20 % (April, May, June) and 5.8 % (September, October, November) of wet-season run-off is stored by the dams, which is a doubling of the storage in the reference period for the both rainy seasons. These numbers also show that the first rainy season generates less run-off than the second, as is also shown in Fig. 4b. It should be noted the average storage for the second

Table 4 Percentage of months (i.e. of all the Aprils, Mays etc.) where discharge is below the 16 percentile low flow at Melka Guba, for measured historic discharge (1972–1976 and 1987–2006), and two sand dam strategies

Scenario	% of time below the 16th percentile		
	No dams	Moderate strategy	High strategy
April	18.2	18.2	22.7
May	17.4	17.4	17.4
June	18.2	18.2	18.2
Sept	18.2	18.2	27.3
Oct	18.2	18.2	18.2
Nov	18.2	18.2	22.7

Values printed in bold indicate higher values as compared with the situation without dams

Table 5 Percentage of months where discharge is below the 16th percentile at Melka Guba using HadCM3 scenarios and two storage strategies for the period 2036–2065

Model	HadCM3 - no dams			HadCM3 - moderate strategy			HadCM3 - high strategy		
	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2
CC Scenario									
April	36.7	46.7	23.3	43.3	56.7	26.7	50.0	63.3	36.7
May	16.7	36.7	23.3	16.7	36.7	23.3	23.3	46.7	26.7
June	3.3	43.3	23.3	3.3	43.3	23.3	3.3	53.3	23.3
Sept	40.0	46.7	43.3	40.0	53.3	50.0	46.7	60.0	50.0
Oct	40.0	43.3	46.7	43.3	43.3	50.0	46.7	43.3	50.0
Nov	43.3	43.3	40.0	50.0	46.7	46.7	50.0	50.0	46.7
Paired t test, $P(T \leq t)$, one tail				0.046	0.055	0.020	0.006	0.005	0.015

Figures printed in bold indicate higher values as compared with the situation without dams

rainy season is heavily influenced by 1 year with 100 % storage, while the range for the other years is from 1 to 10 %. When excluding the outlier, the average storage becomes 2.6 %.

3.2 Household water availability and use

The results from the survey show 279 households without access to water from a sand dam (further referred to as No dam HH), and 37 households with access to water from a sand dam (further referred to as Dam HH). Dam HH use on average 635 l of water per week in the dry season for the five different uses, compared with 498 l for No dam HH.

The results of the household survey indicate that nearly all households need more water in the months January to March (Fig. 5) under current circumstances. The water demand decreases when the rainy season starts in March. During the second dry season the households do not indicate they demand more water. The survey results also reveal that Dam HH respondents use more domestic water (for drinking, cooking, washing) than No dam HH: 635 compared with 498 l, but do not spend more time collecting it (Fig. 6). The time spent on collecting water is comparable for both HH types, because the walking time to the source decreased for Dam HH. Dam HH would save 26 min per person per day to collect

Table 6 Percentage of months where discharge is below the 16th percentile at Melka Guba using ECHAM5 scenarios and two storage strategies for the period 2036–2065

Model	ECHAM5 - no dams			ECHAM5 - moderate strategy			ECHAM5 - high strategy		
	B1	A1B	A2	B1	A1B	A2	B1	A1B	A2
CC Scenario									
April	33.3	30.0	46.7	33.3	30.0	46.7	36.7	43.3	46.7
May	30.0	33.3	43.3	30.0	33.3	43.3	30.0	33.3	43.3
June	23.3	30.0	43.3	23.3	30.0	43.3	23.3	36.7	50.0
Sept	30.0	30.0	36.7	30.0	30.0	36.7	33.3	30.0	46.7
Oct	16.7	23.3	33.3	16.7	23.3	33.3	20.0	23.3	36.7
Nov	23.3	26.7	36.7	23.3	26.7	36.7	26.7	26.7	36.7
Paired t test, $P(T \leq t)$, one tail				n.a.	n.a.	n.a.	0.025	0.101	0.055

Figures printed in bold indicate higher values as compared with the situation without dams

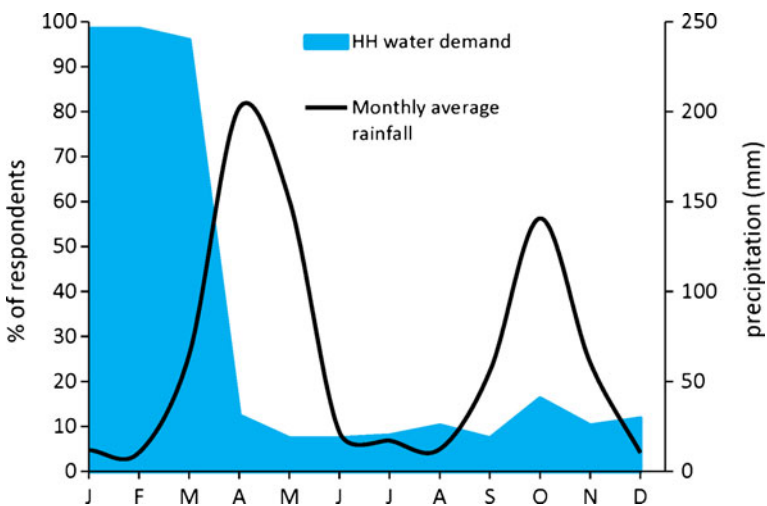
Table 7 Percentage reduction in wet season discharge with the high storage strategy for the baseline period for the baseline period and 2036–2065 HadCM3 A1b

Period	April–May–June			September–October–November		
	avg. storage (%)	5th perc.	95th perc.	avg. storage (%)	5th perc.	95th perc.
1972–2006	9.94	0.67	31.55	3.11	0.50	4.42
2036–2065	19.88	1.12	47.69	5.81	0.94	5.68

the same quantity of water as used by No dam HH. This is in line with findings of the evaluation on economic and health impacts of water supply and sanitation (WHO 2007). The WHO (World Health Organisation) study assumes time savings of 30 min per person per day for improved water supply.

Livestock breeding is the main activity in the districts. The survey data shows that Dam HH respondents have, on average, more cows (*Bos indicus*) and goats (*Capra hircus*) than No dam HH (23 cows and 13 goats, compared with 9 cows and 8 goats). However, Fig. 6 shows there is no significant difference in the time spent on watering livestock.

The herd acts as a savings account for the farmers' family. The primary reason to sell animals is the need to obtain money (65 % of all respondents). The results of the survey show that the respondents prefer to buy and sell cattle, followed by goats. Reduced water availability and reduced grazing grounds for livestock (both 10 % of all respondents) are the secondary reasons to sell cattle. The respondents were also asked about their decision making related to buying livestock and the water sources they use. People who indicated that they will never buy livestock live on average 2 h from a water source. People who answered that they would buy livestock if water availability improves have to walk 1.46 h on average to a water source. Those who indicated they would buy extra livestock if more fodder was available live on average 1.40 h from a water source. While this may indicate that distance to water sources, which can serve as a proxy for water security, influences the decision whether to buy livestock, these differences are statistically not significant.

**Fig. 5** Percentage of respondents who indicated more water was needed per month (left axis,) and the average rainfall in the Dawa catchment (right axis)

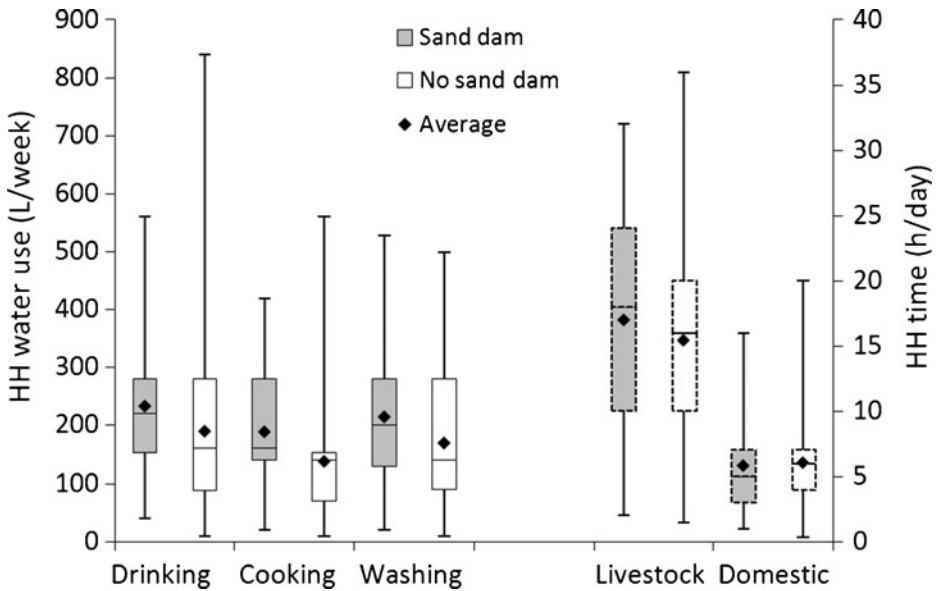


Fig. 6 Box plots of mean dry season household weekly water use (*left axis*), and daily time spent on getting water for livestock and domestic use (*right axis*), for households with (Dam HH) and without access to water of a sand dam (No Dam HH) The boxes have lines at the lower quartile, median, and upper quartile values. Whiskers extend from the lower quartile and upper quartile to the most extreme values

The monitoring network at a sand dam shows that the reservoir is replenished in April, May, June and in September, October, November, and depleted during the dry season (Supplementary material E). This is in line with the average monthly discharge as shown in Fig. 4. Water levels vary between 1.8 m and 5.6 m below the surface; thus the reservoir stores 3.8 m of water. Recharge takes place in a short period of time during the rainy season. Most recharge takes place in November and April, but there are also several small recharge events, for instance between August and October 2011. After the rainy season, from June and December onwards, water levels drop slowly (over the course of, respectively, 101 and 53 days), representing household water use, seepage, and evapo-transpiration.

4 Discussion

4.1 Effects of climate change scenarios on catchment hydrology

The climate scenarios for the Dawa catchment show, over the period 2036–2065, rising temperatures up to 2 °C for the A2 and A1b scenario, and 1.6 °C for the B1 scenario, compared to the current climate. Average precipitation is projected to increase slightly and the variability between years is projected to increase. When using these scenarios as input to the hydrologic model of the catchment, we see a strong increase in the number of months where modelled discharge falls below the current minimal environmental flow requirements, as defined in Section 2.6. This increase ranges from 0 up to a 29 %. These differences in modelled low flow occurrence might be the result of differences in the projected precipitation and temperature data of the climate models and scenarios, in combination with differences in the calibration between the models based on, respectively, the Echem and

Hadley model runs. The modelled discharge using the Echem model and baseline climate data (Fig. 4) is 5 to 12 m³/s lower for the months June to September as compared with discharges simulated using the Hadley model and baseline climate data. These numbers show the uncertainty involved in using single models and scenarios. Therefore there is a necessity to include multiple scenarios, GCMs, and if possible multiple models, to provide ranges of discharges for decision makers (e.g. Ward et al. *in press*). The combination of a small increase in precipitation and a large increase in temperature leads to a reduction in modelled discharge, leaving less water available for use. These results indicate that climate change is an important pressure which will manifest on the longer term on these already stressed communities, as addressed by Knox et al. (2012) and Abaya et al. (2011).

4.2 Water storage strategies using sand dams

For current climatic conditions, this study shows that the moderate sand dam strategy does not lead to changes in the number of months with simulated discharge below the environmental flow requirement. The high strategy, however, shows an increase of 4 % to 9 % in the occurrence of low flow in the months April, September and November. When combining the two storage strategies with climate change scenarios for the period 2036–2065, the number of low flow months increases. The largest impact is at the start of the rainy season, when dams are empty, and the discharge is relatively low compared to the discharge of the other months of the rainy season (Fig. 4).

For the moderate dam strategy, this increase in low flow is limited: only the model based on Hadley climate scenarios shows an increase in the number of months where the environmental flow is not reached. For the Hadley model half of the simulated months for the three climate scenarios and the moderate dams strategy show an increase in flows below the environmental flow requirement. For the high strategy, low flow increases between 0 % and 13 %, compared with the situation without the construction of dams for period 2036–2065. The simulations with Hadley B1 data for June, show a decrease in low flow occurrence of nearly 15 %, compared with the historic discharge, while all other months show equal or increased low flow occurrence. This might be caused by relatively high average precipitation in this scenario as compared with A1B and A2. The model calibrated on Hadley data shows larger impacts as compared with the model calibrated on Echem data. In some cases environmental flow is not met during 60 % of the time as compared with 47 % without the implementation of the dams, indicative of the potentially substantial impacts of the combination of sand dam strategies with these climate scenarios on low flows. However, at the same time, our results show that the downstream effect of sand dams on discharges is smaller than the effects of climate change on discharge.

Comparing the percentages of below environmental flow occurrence in Table 5 with the percentage of wet-season discharge stored by dams in Table 7, it is possible to arrive at different conclusions concerning the downstream effects. While increases in the frequency of discharges below environmental flow suggest substantial downstream impacts for some of the climate scenarios, only about 4.5 % of the total yearly wet season discharge is stored in the sand dams (19.9 % and 5.8 % for the two rainy seasons, respectively), suggesting only a modest downstream impact. Especially when taking into account that the value for the second rainy season is heavily influenced by 1 year with 100 % storage. The environmental flow indicator is very sensitive to relatively small changes in discharge when looking at ephemeral river systems. Therefore, it only captures one dimension of the downstream impacts important to decision making: the occurrence of relatively low flows. The reduction in wet-season flow should therefore be added to the evaluation of the results when assessing downstream impacts, in order to obtain a more complete picture of the effects.

19.9 % of the total discharge at Melka Guba is stored in the sand dams during the first rainy season, assuming the most extreme climate change scenario (A1b), in combination with the high strategy for the period 2036–2065. This number should be compared with 9.3 % storage for the reference period (1972–2006). The storage percentage of the high strategy in the second rainy season also doubles to 5.8 %, indicating that over 94 % of the available discharge still passes the gauging station Melka Guba. These figures are comparable to the results of Aerts et al. (2007), who did a similar catchment-based analysis in Kenya. They found a reduction in simulated discharge ranging between 1.8 % and 3.0 % for one of the rainy seasons, and a decrease between 3.8 % and 20 % for the other rainy season. The findings of our study are lower than the findings of de Fraiture (2007) and Bouma et al. (2011), who reported reductions in downstream discharge of 32 % and 11 % respectively. For another comparison, Schreider et al. (2002) explored the relation between the reduction in observed flow in an ephemeral river in Australia and the presence of upstream storage. In their case, the total dam volume is as large as 60 % of average annual discharge, and the discharge reduced by a factor of 4 to 6 of the increased dam volume. The results of our study show that modelled discharge decreases by a factor of 3.4 with a total dam volume of 0.3 % (2,190 dams) of average annual discharge.

Wisser et al. (2010) conducted a global scale analysis of the impact of small reservoirs on discharge. They assumed total maximal storage per basin using crop water need and available run-off. For 2963 basins, water storage led to a reduction of yearly discharge at the river mouth, of on average 18 %, for the period 1998–2002. For smaller basins the reduction in discharge was larger, up to 80 %. This is in line with results from Nyssen et al. (2010), who found a reduction of 81 % in runoff in a catchment of 200 ha where 282 small dams were constructed. When comparing these numbers with our results, the impacts reported by Wisser et al. and Nyssen et al. are much higher than our results, with a decrease of maximal 4.5 % in wet season discharge. One of the main differences is the assumed larger total storage capacity of the reservoirs compared to the catchment size by Wisser et al. (2010) and by Nyssen et al. (2010). This high density of storage structures and high total storage capacity is not realistic for our case study area. The population density is too low to require high amounts of storage. And when taking into account the construction costs, which are about 12,000 \$ per dam, or 0.40 \$ per m³ over the lifetime of a dam (Lasage and Verburg *in press*), the investment per capita would become high. Furthermore, the local populations water demand to achieve water security in the dry season is also relatively limited and needs less storage compared to the studies of Wisser et al. (2010) and Nyssen et al. (2010).

Given the uncertainties in the modelling approach it is also important to continuously monitor downstream impact during the implementation of water storage projects. If the impacts of the dam construction or climate change are larger than anticipated during the model-based assessment, this will become clear over the years when the dams are being constructed. The advantage of building small scale constructions is that planning can be changed relatively easily if the impacts turn out to be different from what was expected (Adimo et al. 2012), enabling adjustments if necessary.

4.3 Management and use of sand dams by households

The household survey shows that households with access to water from sand dams use more water in the dry season, spend less time on water-related activities, and are more water secure. A relatively small proportion of the households that participated in the survey were actually using sand dams for their water supply, as only a few sand dams have been constructed in the area. This leads to some uncertainty about the relationship between

changes in household water availability, household water needs, and the wider effects on the households. The difficulties in measuring changes at the household level of water harvesting projects have been identified by Kunze (2000). We do not see a clear difference in the households' economic situation or the time spent on other activities between those households with improved access to water and those without, although research suggests that such relationship does exist (Pachpute et al. 2009; Lasage et al. 2008; Katsi et al. 2007; Hatibu et al. 2006). The survey shows that almost all respondents indicate that they have more water available during the dry season to support their main economic activities. Water is therefore an important economic driver for rural communities in the Dawa region. Our study gives insight in changes in water availability, additional information is necessary on related costs and benefits as indicated by Bouma et al. (2011). The combination of data on water levels in the reservoir behind the sand dam and water use by the communities will help to determine the specific storage capacity of the dams and the factors which influence this. Insights based on these dams can be used in the future to develop a method to determine available water, based on the water level in the extraction well. Enabling better sand dam water management by the communities themselves is in line with Baye et al. (2012) who conclude that local communities should be involved in all steps of a project and also should have the skills to operate and maintain the structures.

5 Conclusion and recommendations

Our study shows small scale water storage measures called 'sand dams' are feasible as an adaptation strategy to deal with scarce water resources and to improve water security, now and under climate change. The approach combines a hydrological model with local scale survey and hydrological data in the Dawa catchment in Ethiopia. The modelling results show that constructing large number of sand dams (to meet current and future water demands in the area) only has modest downstream impacts, reducing downstream flow by 19.9 % and 5.8 % during the two rainy seasons under the most extreme climate change scenario (A1b), compared to current downstream flow. For the other climate scenarios the reduction is less. Together with the positive local impacts shown in the survey results, like reduced walking time to water sources and an increase in water availability, this shows that sand dams are, from a hydrological viewpoint, a viable way for supplying drinking water in this region. The impacts of climate change on average yearly downstream discharge vary from an increase of 1 % to a decrease of 40 %. The small scale nature of the measure also allows for adjusting the total number of reservoirs during implementation, making it an adaptive approach. If the climate develops in a different than currently projected, or if changes in demand occur, these can be taken into account during implementation.

The approach, uses public data and is suitable to evaluate general changes on a monthly time scale. The same approach can help to evaluate a wider range of adaptation measures necessary to deal with the projected impacts of climate change and water security in large parts of the semi-arid region.

Using these small water harvesting structures a contribution can be given to the universal access plan of the Ethiopian government (MoWR 2005; MoWR 2009), which, amongst other things aims to reach the Millennium Development Goal 7 (i.e. to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation). After careful assessment as conducted in this study, it is likely that water harvesting is also applicable in comparable semi-arid regions in the world to improve water security on the short and long term.

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