Sustainable agricultural intensification at community-managed reservoirs in the Volta basin

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Abstract

Dry season food production has been promoted in the West African Volta basin since the 1960s through the construction of hundreds of dams on minor rivers to create small, community-managed reservoirs. The benefits of these reservoirs for smallholder crop farmers are disputed in academic literature. There is little concrete evidence regarding their effectiveness at increasing dry season crop production or improving human well-being (HWB) outcomes for local households. Construction of reservoirs remains a regional policy priority, with Burkina Faso increasing investments in dams under its 2016-2020 national development plan and Ghana committed to a 'One village, One dam' initiative for 2017-2024. Stronger evidence of the conditions under which community-managed reservoirs provide the intended benefits and how to make benefits sustainable could help ensure the success of existing and future investments. This thesis developed and tested low-cost, transferable methods for monitoring the distribution and water storage dynamics of reservoirs in the Volta basin and their impacts on dry season crop production across different socio-economic and environmental contexts. Qualitative research at four community-managed reservoirs in Burkina Faso and Ghana was used to assess farmer perceptions of the benefits and HWB outcomes of access to reservoir water in relation to other natural resources in reservoir landscapes. Results show that remotely sensed imagery can be reliably used to monitor reservoir water availability, but challenges remain over very small reservoirs. Across the Volta basin, there is high spatial and seasonal variability in reservoir water availability to farmers. Nearly half of small and medium reservoirs, i.e. those smaller than 10 Mm^3, are actively used for irrigation during the dry season. Uptake of irrigation at these reservoirs is more likely where there is better water availability (larger volumes, higher runoff rates, fewer dry months), better local market access (proximity to towns), greater pressure on local water resources (higher population and cattle densities, poorer water quality), and where there are marginally fewer human

resources available (slightly lower labour availability and literacy rates). Farmers at the four case study sites characterised their landscapes as multi-functional supplying a diversity of ecosystem services (ES) and disservices (ED). ES were highly valued by local farmers for their contribution to multiple dimensions of HWB, however the importance of specific services varied significantly with farmer socio-economic profile. Making the dry season benefits of reservoirs accessible to farmers is part reliant on the surrounding ecosystem providing adequate amounts of ES that support crop production, food storage and cooking, and help maintain farmer health, highlighting the importance of integrated landscape approaches to reservoir design and management. Potential trade-offs in HWB outcomes and between households needs to be carefully considered in ecosystem management decisions in reservoir contexts to secure sustainable food production and development outcomes.

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List of Acronyms

CAADP	Comprehensive African Agriculture Development Programme
ED	Ecosystem disservices
ES	Ecosystem services
GSW	Global Surface Water
HWB	Human well-being
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MEA	Millennium Ecosystem Assessment
NDVI	Normalised difference vegetation index
NDWI	Normalised difference water index
MNDWI	Modified normalised difference water index
RMSE	Root mean square error
SDG	Sustainable Development Goals
TAI	Targeting agricultural innovations and ecosystem services in the northern Volta basin (a CGIAR-funded project)
WRD	World Register of Dams

1. Introduction

1.1. Problem definition

Growth in population and per capita income are increasing demand for food worldwide (Godfray et al., 2010; Tilman et al., 2011). Meeting this demand will require a combination of increased food production, removal of barriers to food access, and reduction of food waste (Godfray and Garnett, 2014). Food production can be increased on existing agricultural land through intensification or by converting new land into agriculture. Irrigation is a promising route to agricultural intensification in water-limited areas and is needed to close yield gaps across sub-Saharan Africa (Mueller et al., 2012).

Agricultural intensification, and expansion, has been promoted in the West African Volta basin since the 1960s through the introduction of hundreds of small, community-managed reservoirs. Small reservoirs can reduce agricultural vulnerabilities to rainfall variations (Douxchamps et al., 2014), facilitating crop, livestock and fishery-based livelihoods (Venot and Cecchi, 2011). At present there is very little information on the quality, quantity, location or timing of water available to farmers from reservoirs in the Volta basin, the effect of these supplies on irrigated crop production, or the sustainability of these agricultural intensification systems. The small number of studies that exist show that crop productivity in small reservoir-irrigated systems is consistently much lower than its potential (Faulkner et al., 2008; Mdemu et al., 2009; Ofosu et al., 2010; Poussin et al., 2015) and that the presence of a reservoir does not always lead to irrigated crop production, e.g. 73 out of 126 reservoirs in Upper-East Ghana had no irrigation activity in either 2006 or 2007 (Birner et al., 2010). Research indicates that river dams can have extensive negative impacts on environmental water flows (Vörösmarty et al., 2010), biodiversity and ecosystem functioning (McCartney, 2009) and human health (Boelee et al., 2012) while unequal access to reservoir water can increase the gap between rich and poor households (Sally et al., 2011). It is therefore unclear how sustainable these intensification mechanisms

are and no surprise that the benefits of small reservoirs in the Volta basin are hotly disputed in academic literature (Venot and Krishnan, 2011).

This controversy is underpinned by a scarcity of comparable, reliable data on reservoir locations, capacities, uses and beneficiaries across the basin (Cecchi et al., 2009; Douxchamps et al., 2014), making it difficult to monitor how water resources in reservoirs, crop production and smallholder livelihoods are linked across time and space. We do not know if, when or to what extent community-managed reservoirs lead to increases in dry season crop production, nor how access to reservoir water impacts on the well-being of smallholder farmers. Provision of other natural resources and ecosystem processes in reservoir landscapes may be equally or more important to local farmer livelihoods and well-being, since agriculture depends on a multitude of ecosystem services (ES) (DeClerck et al., 2017; Power, 2010; Zhang et al., 2007) and rural households in the Volta basin have been found to depend on multiple ES (Sinare et al., 2016). Nature-people interactions in reservoir contexts require more attention to determine how to minimize trade-offs between farmers and human well-being (HWB) outcomes during and after dam intervention planning. Construction of small, community-managed reservoirs is an ongoing priority for donors and national government (CPESDP, 2017; Fowe et al., 2015; PNDES, 2016; Poussin et al., 2015) as a way to stimulate agricultural production and decentralise irrigation systems (Burney et al., 2013; Venot and Cecchi, 2011). Therefore it is important we understand under what conditions these reservoirs can provide the intended food production and HWB benefits.

1.2. Research aim and objectives

The **central research question** addressed in this thesis is: Under what socio-economic and environmental conditions can community-managed reservoirs effectively and sustainably increase dry season cropping and local farmer well-being?

Through a combination of remotely sensed imagery and geospatial data analysis at the Volta basin level, combined with in-depth fieldwork (interviews, focus groups, transects and land use surveys) around reservoirs used by smallholder irrigators, specific **research objectives** were to:

1. Map the spatial and intra-annual distribution and relative sizes of reservoir water supplies across the Volta basin;
2. Test methods for detecting the presence-absence and extent of irrigation around small to medium sized reservoirs in the Volta basin, using remotely sensed data;
3. Explore potential socio-economic (e.g. population density, household income, market access) and environmental (e.g. reservoir shape, reservoir volume, irrigation infrastructure, soil quality, local hydrology) factors driving the use of small to medium sized reservoirs for irrigation in the Volta basin;
4. Assess the ecosystem services and disservices supplied in and around small to medium reservoirs and their importance to human wellbeing as perceived by local smallholders, using data collected at four case study sites: Bidiga and Ladwenda in Burkina Faso, and Binaba and Tanga in Ghana.

The following sections present the theoretical and empirical context for this research and analytical frameworks applied.

1.3. Theoretical context

1.3.1. Community-managed reservoirs

Over the last few decades, there has been a global shift from top-down to bottom-up development interventions to manage water (Mehta and Movik, 2014) and other natural resources (Crescenzi and Rodríguez-Pose, 2011). This shift comes in response to difficulties in mobilising citizens to sustainably govern their common-pool resources (Nagendra and Ostrom, 2012) and concerns about the effectiveness of top-down regional development policies (Pike et al., 2007). Bottom-up interventions tend to be better aligned with local needs (Crescenzi and Rodríguez-Pose, 2011) and decentralise control over resources, empowering local communities to sustainably manage their resources. However, management of common-pool resources to ensure sustainable social, economic and environmental outcomes is challenging (Kimbrough and Vostroknutov, 2015; Nagendra and Ostrom, 2012; Ostrom, 2007). It requires collective action to enable multiple citizens to benefit from but not over-exploit the resource, and avoid resources falling victim to the 'tragedy of the commons' (Hardin, 1968). Several studies have shown that decentralised water resource management interventions, also referred to as 'integrated water resource management' approaches, have had mixed success in achieving positive ecological and socio-economic outcomes in African contexts (Mehta and Movik, 2014).

Dams designed to create locally managed reservoirs are an example of a development intervention that transfers responsibility for water resource management away from national government and towards local communities. These infrastructures are designed to capture and store runoff from rainfall and groundwater flow. Definitions of small reservoirs vary, but typically refer to those reservoirs that are used for small-scale food production, predominantly supporting smallholder farmers (Senzanje et al., 2012). Small reservoirs are defined in this thesis as any surface water body formed by damming a stream, where the water body has a maximum capacity of less than 1 million m^3 (Mm^3)

consistent with the International Commission on Large Dams (ICLD, 2016). Medium sized reservoirs are defined as those with a maximum capacity of between 1 and 10 Mm^3, many of which are still small enough to be community-managed and used predominantly by smallholders. Both small and medium sized reservoirs, *i.e.* those smaller than 10 Mm^3, are therefore of interest to this thesis.

Despite numerous investments in small dams across the global south (Venot & Krishnan 2011) and specifically the Volta basin (Cecchi et al., 2009; Leemhuis et al., 2009) in recent decades, there are currently very few data available on the distribution, sizes, temporal dynamics or uses of small or medium sized reservoirs. The World Register of Dams (WRD) holds records for 58,402 dams worldwide with an average water holding capacity of 16,101 km^3 (International Commission on Large Dams 2016). Small dams, such as those with a dam height of under 15 m, are not registered in the WRD and no global datasets documents these infrastructures. Data on reservoir locations and capacities for parts of the Volta basin are available from several sources, including in-country water ministries and previous research projects that document local distributions, such as Liebe et al. (2005). The Burkinabé government invested heavily in small reservoirs and irrigation infrastructure following Thomas Sankara's revolution in the 1980s (Harsch, 2014) (see Figure 1), while in northern Ghana and in Mali, governments have prioritized similar investments over the last few decades (Boubacar et al., 2005). Yet, the number, locations, acquisition dates, and size estimates of these reservoirs are highly inconsistent across sources (Venot et al., 2012). For example, at many sites where reservoirs are documented in official records, no reservoir is visible on satellite imagery, and reservoirs detectable on imagery are not always registered in official datasets (Cecchi et al., 2009; Venot et al., 2012). In addition, information on reservoir water use for irrigation or other activities is largely undocumented, and none of the regional datasets provide information on the seasonal or inter-annual variability in reservoir water supplies to highlight places and

months when farmers are at risk of water shortages. These gaps make it difficult to include small and medium sized reservoirs in water accounting or impact assessments, to better understand how effective small-scale dam interventions are for sustainable rural development in the region.

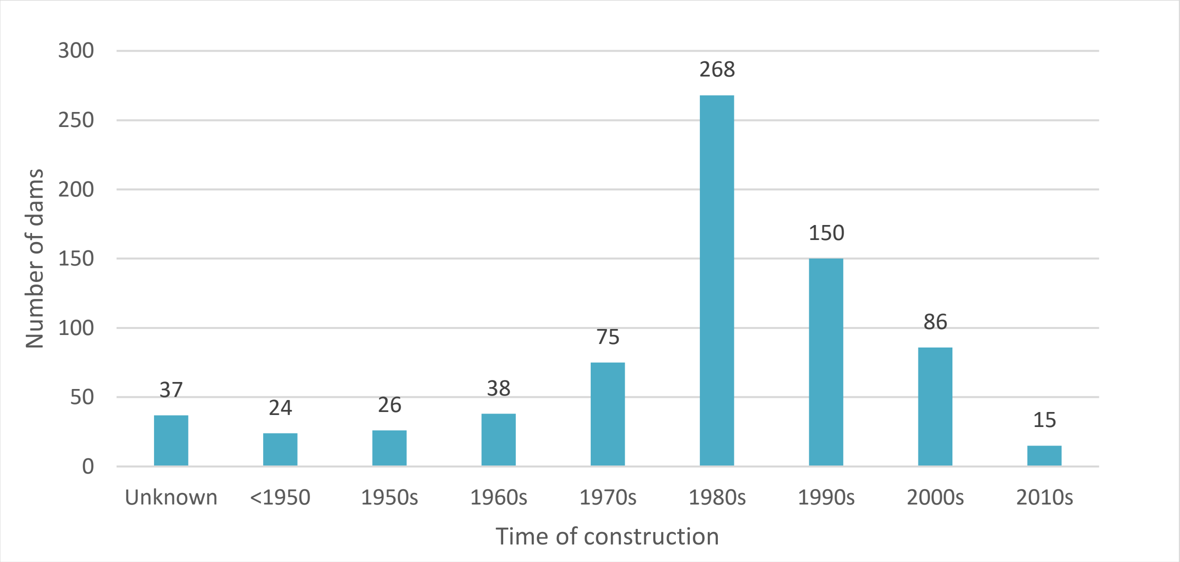

Figure 1: Trends in small reservoir (<1 Mm^3) construction within the Volta basin, for Burkina Faso. Based on data for 1990-2011, received from Direction Générale des Ressources en Eau (pers. comm., February 2016).

1.3.2. Dry season reservoir-irrigated cropping

In seasonally dry areas where variable or inadequate water supplies are a constraint to crop production, interventions to store rainfall and provide year-round water supplies can help farmers to mitigate dry spells and practice double cropping (Birner et al., 2010; Rockström and Falkenmark, 2015; Wisser et al., 2010). Irrigated cropping is a form of agricultural intensification in these water limited areas (Mueller et al., 2012; Thakur et al., 2015) and facilitated by small reservoirs (see Figure 2). Water stored in reservoirs can make it easier for crop farmers to manage variability in rainfall through supplemental irrigation of rainfed crops, increase cropping intensity through dry season cropping, and make more productive use of floodplains by regulating flood pulses. The potential for smallholder irrigated area expansion at small reservoirs across West Africa, achieved through dry season irrigation, is estimated at 9.1 million ha with potential revenues of $6.0

billion yr^{-1} (Xie et al., 2014). Small reservoirs therefore have potential to be transformative development interventions, shifting subsistence farmers towards productive, profitable farm businesses (Douxchamps et al., 2014).

Figure 2: (a) Manual irrigation, (b) irrigation canal, and (c) view upstream from the dam wall, at Bidiga reservoir in Centre-Est Burkina Faso, 16 February 2018.

Yet evidence is inconclusive regarding the actual impact of reservoirs on irrigated food production in the Volta basin. Empirical data on irrigated cropland associated with community managed reservoirs in the Volta basin are available for some reservoirs from micro-level studies. Irrigated cropland covers a small portion of the irrigable area at some reservoirs (Wekem, 2013) while irrigated crop productivity is generally found to be much lower than its potential (Faulkner et al., 2008; Mdemu et al., 2009; Poussin et al., 2015). For example, farmer recorded irrigated tomato yields ranged from 1 to over 50 tons per ha between reservoirs located in northeastern Ghana, averaging nearly 20 tons per ha (Ofosu

et al., 2010) and highlighting the potential for increases at many farms. No irrigation activities were identified at 42% of reservoirs surveyed in Upper-East Ghana (Birner et al., 2010). Clearly, not all reservoir investments in the Volta basin are successful in increasing crop production and the magnitude of the impact, in terms of cropped area, productivity and associated extra food, could be improved.

1.3.3. Irrigation adoption

Farmer adoption of reservoir irrigation depends on many factors. Previous studies from the Upper East region in Ghana indicate that a small reservoir is more likely to be used for irrigation where reservoirs are relatively large, have better reservoir maintenance arrangements, and where adjacent land has better soil quality (Birner et al., 2010). Research from the same region shows that male farmers and those with higher education and income levels are significantly more likely to practice reservoir irrigation (Wekem, 2013). Cultural factors are likely to also play a part. Research from northern Burkina Faso showed that Peulh farmers, traditionally nomadic herders, are significantly less likely than other ethnic groups to partake in reservoir irrigation (Ayantunde et al., 2018). The same study found that irrigation around small reservoirs is more likely to be practiced by larger households and those with larger farm areas.

It is unclear if these results hold across the Volta basin and difficult to determine since data on reservoir-irrigation status is not readily available. Other factors identified in studies with smallholders outside the Volta basin may also influence farmer irrigation adoption, such as previous experience with growing crops under irrigation and marketing high value crops (Kulecho and Weatherhead, 2006). Even the shape of a reservoir and its design - e.g. lined or unlined, underlying bedrock, and quality of canals – may affect irrigation adoption. Shape determines how much water it can hold, and how much water is lost to evaporation and seepage (Liebe et al., 2005), while reservoir perimeter length impacts on the potential distance between farmland and reservoir water. A shorter

perimeter length means a smaller amount of farmland can be located within an easy carrying or pumping distance from the water. Reservoir geometry thus influences irrigation water availability and accessibility for farmers, and may affect irrigation uptake but no studies to date have assessed this relationship.

1.3.4. Sustainable intensification through irrigation

Whether or not a dam intervention is successful as a development intervention is measured in this thesis in terms of whether it is effective at leading to dry season irrigated cropping, and whether this irrigated cropland is sustainable. Dry season irrigated cropping is considered sustainable if it increases the amount of food produced on existing agricultural land while maintaining or reducing the negative environmental impacts of this food production. This is consistent with the concept of ‘sustainable intensification’ (Baulcombe et al., 2009; Pretty and Bharucha, 2014).

The notion of sustainable intensification of agriculture emerged in the 1990s (Weltin et al., 2018) and gained prominence since release of a Royal Society report advocating its uptake (Baulcombe et al., 2009). While there is much debate on how to put sustainable intensification into practice (Garnett et al., 2013; Loos et al., 2014; Petersen and Snapp, 2015; Poppy et al., 2014b), some concrete ideas from Godfray & Garnett (2014) include taking land with a high potential biodiversity value and low agricultural potential out of production (‘back to nature’), changing farming practices on some agricultural land to better support wildlife and minimize environmental impacts (e.g. conservation agriculture, agro-ecological approaches) even if this means reducing yields, and working to establish multifunctional landscapes where agricultural and non-agricultural land are arranged and managed to conserve biodiversity and provide multiple ES. The latter idea is consistent with calls for an ES approach to increasing food production (Robertson et al., 2014) including among smallholder African farmers (Pretty et al., 2011; Vanlauwe et al., 2014), which recognizes agriculture as a provider of ES such as food and

fibre whose provision depends on multiple ES generated both on and off-farm (DeClerck et al., 2017; Power, 2010; Swinton et al., 2007; Zhang et al., 2007). This body of work argues that intensification will only be viable in the long-term and ecologically sustainable if a diversity of ES are maintained across the agricultural landscape. Here, 'landscape' refers to spatial, agricultural and ecological boundaries that can be used to help define and manage trade-offs between conservation and agricultural production targets, building on definitions from landscape ecology (Reed et al., 2015).

This study considers two dimensions of reservoir irrigation sustainability: environmental sustainability in terms of crop water productivity, and sustainability in terms of HWB outcomes considered through an ES lens, discussed in the next two sections.

1.3.5. Water productivity

Producing more 'crop per drop' - food per unit of water - improves the sustainability of water resource use in agriculture (Brauman et al., 2013). Globally, irrigation is the single largest user of freshwater (FAO-AQUASTAT, 2018). Finding ways to use it more productively will help ensure we can meet future demands on water for agricultural and other uses (Elliott et al., 2014). Increasing water productivity on existing cropland will help close yield gaps while reducing the need for expansion of agricultural land to meet future food demands (Brauman et al., 2013). This is important since conversion of natural lands to agriculture is considered the number one driver of biodiversity loss, and of the concomitant loss of ES (MEA, 2005) and further expansion is considered risky at a planetary level because it "may seriously threaten biodiversity and undermine regulatory capacities of the Earth System" (Rockström et al., 2009).

Crop water productivity is a measure of food output per unit water input, typically expressed in kg per m^3. Water productivity is confusingly used interchangeably with water use efficiency in the literature (van Halsema and Vincent, 2012). Agronomists have long

used crop water use efficiency to mean plant output produced per unit of transpiration or evapotranspiration, akin to water productivity, while irrigation engineers define it as how much available water is delivered to a crop after water losses (Molden et al., 2010). This thesis follows van Halsema and Vincent (2012) who suggest that crop water productivity in irrigated croplands is defined as food output per unit water input, while water use efficiency is used to refer to irrigation water efficiency.

Water productivity is a limited metric for assessing environmental sustainability of irrigated cropland because there are a diversity of potential negative environmental impacts. Irrigation can lead to loss of soil fertility due to waterlogging and salinity, over-abstraction of water depleting environmental flows, and increased agrochemical inputs (Holy, 1993; Hussain and Hanjra, 2004). Yet improvements in water productivity have potential to not only increase food output, but also reduce losses to natural water flows and thus help maintain healthy ecosystems and associated services that benefit local livelihoods (Molden et al., 2010). Water productivity is a particularly useful measure in areas of agricultural water scarcity, as is the case for dry season irrigators in the Volta basin who depend on ephemeral reservoirs. Increasing water productivity in these areas can mean more households are able to irrigate and higher net profits (Molden et al., 2010).

1.3.6. Ecosystem services and human well-being

Where a reservoir is used for irrigation, the impact on local farmer well-being is likely to depend on the distribution of land and water resources, and how HWB is measured (Hussain and Hanjra, 2004). While there is no standard definition of HWB (Summers et al., 2012), there is general consensus that HWB is multi-dimensional and comprises both objective (widely accepted basic human needs) and subjective (individual assessments of one's own well-being) elements (Stiglitz et al., 2009).

In ES literature, ecosystems are recognized as providing a diversity of benefits to

humans that maintain or enhance their well-being (Díaz et al., 2015; MEA, 2005). ES, also referred to as 'Nature's Contribution to People' (Díaz et al., 2015), refer to the "benefits people obtain from ecosystems" (MEA, 2005). These services may be classified into provisioning (including food, water, fibre), cultural (such as recreational, spiritual, emotional benefits of exposure to nature), regulation and maintenance (for example, soil nutrient cycling, flood regulation, and conserving habitat for species reproduction) (Haines-Young and Potschin, 2013). The Millennium Ecosystem Assessment (MEA) suggested HWB is composed of five dimensions: material, security, health, social relations and freedom (MEA, 2005), and the more recent Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) broadly supports this definition (Díaz et al., 2015). Each ES maps onto one or more of these dimensions. The benefit of the MEA and IPBES frameworks for studying HWB is that they explicitly recognize nature's contributions to HWB. However, they omit some important elements of HWB, including subjective well-being (Summers et al., 2012).

Evidence of reservoir irrigation impacts on farmer well-being in the Volta basin is limited to micro-studies and tends to focus on household income as the outcome metric. For example, Katic et al. (2014) show that revenues from irrigated production increased substantially after small reservoir construction at four sites in Burkina Faso. Wekem (2013) found that the average income for farmers practicing dry season irrigation at two reservoirs in Upper East Ghana were over 50% higher than for those that do not; though this could reflect that it tends to be wealthier households that have the means to access the inputs required to engage in (high input) irrigated cropping. Conversely, Poussin et al. 2015 found that poor reservoir maintenance, lack of product marketing and poor crop management led to only marginal increases in income for irrigating households at two case study sites in Burkina Faso. These assessments, while useful for understanding the material well-being benefits of reservoir irrigation, do not capture the social, health or subjective dimensions of

well-being. Unequal perceptions of quality of life between people and places with equal income levels has called into question the use of monetary indicators of well-being (Sen, 1999). Relatively little is known about the impact of smallholder farmer access to reservoir irrigation water on holistic measures of HWB in the Volta basin, in absolute terms or relative to other sources of HWB available in the landscape.

Assessing HWB impacts through an ES lens can help understand the distribution and diversity of HWB outcomes and their sustainability. Identifying the impact of ecosystems on HWB in a specific context can help identify trade-offs in HWB outcomes between places and people. ES can contribute to sustainability goals because they focus attention on how HWB can be maintained or improved through biodiversity and ecosystem conservation (Geijzendorffer et al., 2017; Schröter et al., 2017). However, ES provision does not necessarily lead to sustainable outcomes. ES are not a goal in themselves but can be managed with the end goal of sustainability (Schröter et al., 2017) or sustainable intensification (Poppy et al., 2014a). For example, power asymmetries must be addressed to ensure sustainable and equitable ES management (Berbés-Blázquez et al., 2016). Ensuring locally important ES in intensification landscapes continue to meet the needs of a wide range of local stakeholders may help address distributive injustices.

Despite much progress in the last few years regarding the linkages between ecosystems and HWB, relatively few ES assessments have been carried out in semi-arid regions or poverty contexts (Suich et al., 2015). A review of 52 research articles on ES in Africa found that most studies took place in southern or eastern Africa and only a quarter of studies incorporated non-monetary values of ES, focusing on biophysical rather than social dimensions (Wangai et al., 2016). In the Volta basin, ES supplies have been quantified in several micro studies, including soil restoration services provided by termites in Zaï fields in northern Burkina Faso (Kaiser et al., 2017), community uses of woody plant species in Pama reserve, south-east Burkina Faso (Ouédraogo et al., 2014), and

provisioning services provided to communities in Ejisu-Juaben, southern Ghana (Asamoah and Wiafe, 2016). Volta-wide ES supplies and alternative ecosystem management scenarios have been modelled using Co$ting Nature (Mulligan and Van Soesbergen, 2017) and WaterWorld (Willemen et al., 2017). Some studies have considered trade-offs between agriculture and ES, for example in relation to cocoa intensification in southern Ghana (Vaast and Somarriba, 2014). ES valuation research in the Volta basin is scarce and appears limited to just three studies. These include Houessionon et al. (2017), who used choice experiments to explore farmer preferences for ES derived from four agricultural water management interventions in central and southwest Burkina Faso. Sinare et al. (2016) explored livelihood benefits of ES in northern Burkina Faso, by identifying which provisioning services are used for consumption or sale and using the biophysical service supply to gauge the value of these benefits to local households. Finally, Asamoah and Wiafe (2016) explored social (assigned) values for provisioning services and ES sources from the perspective of individuals in local communities and found that values were split along income lines.

The shortage of ES valuations highlights an important gap in understanding the role of ES in contributing to, and ED in detracting from, well-being in the Volta basin. Further research to understand values for ES and ED from a local perspective, and particularly that of farmers as primary land stewards, could help identify locally appropriate and socially just ecosystem management pathways for maintaining and improving local well-being.

1.4. Empirical context

1.4.1. Overview

This thesis focuses on the Volta basin and four case study agricultural landscapes containing small or medium sized community-managed reservoirs located in the seasonally dry central range of the basin (Figure 3). The Volta river basin covers 400,000 km^2 of West Africa, of which 84.5% of the area is contained within Ghana and Burkina Faso while the remaining 15.5% is shared between Togo, Benin, Mali and Cote d'Ivoire.

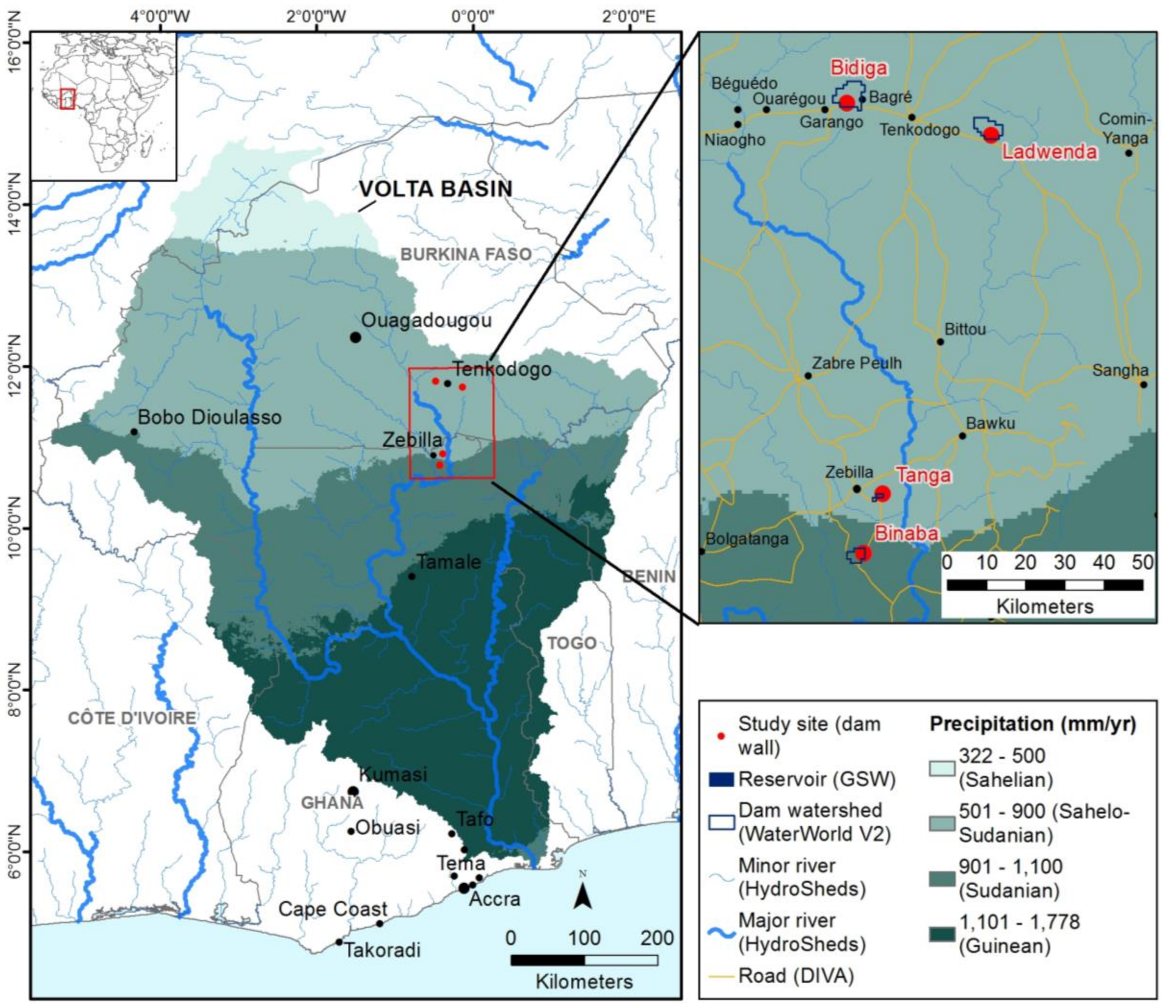

Figure 3: The Volta basin mean annual precipitation and this research's four case study landscapes (Bidiga, Binaba, Ladwenda and Tanga). Precipitation is based on 1970-2000 means calculated from WorldClim V2.0 data (Stephan E. Fick and Hijmans, 2017).

The basin is characterised by a rapidly growing, youth-heavy population and agricultural economies dominated by smallholder farms (Deininger and Byerlee, 2012).

Poor soil quality and physical water scarcity (Lahmar et al., 2012) combined with high levels of food insecurity and sizeable yield gaps (Lemoalle and de Condappa, 2010), makes the need for sustainable intensification as pressing here as anywhere else in Sub-Saharan Africa. The four case study landscapes were selected based on evidence of irrigation activity identified from Google Earth, and to coincide with sites engaged in a Bioversity International led CGIAR Water Land and Ecosystems project in 2015-2016 to facilitate stakeholder engagement. Sites are characterised by gently sloping terrain dominated by cropland intermixed with grassland and sparse tree and bush cover (see Table 1). Rainfall at these sites is 700-1000 mm per yr and bimodal, with mean annual temperatures of ~28 °C. All reservoirs are situated within 30 km of a small market town.

Table 1: Characteristics of case study sites

	Site name (alternative name)			
Characteristic	**Binaba (Asam)**	**Tanga (Tangabote)**	**Bidiga (Bedega)**	**Ladwenda (Lagdwenda)**
Geographic location	10.7797 N, -0.47731 E	10.9169 N, -0.4335 E	11.8160 N, -0.5149 E	11.7423 N, -0.1832 E
General location	Bawku West, Upper East Ghana		Boulgou, Centre-Est Burkina Faso	
Landscape	Undulating hills with gentle slopes. Sparse tree cover on savanna grasslands intermixed with cropland. Tall trees relative to Bidiga and Ladwenda. More woody outcrops at Binaba than other case study sites.		Undulating hills with gentle slopes. Very sparse tree and bush cover on savanna grasslands, intermixed with cropland. Large areas of laterite soils which cannot easily be cultivated.	
Landscape size (reservoir, irrigation scheme, and reservoir catchment with 2 km buffer)	57 km^2	32 km^2	109 km^2	89 km^2
Altitude (HydroSHEDS 15s)	207 m	201 m	281 m	261 m
Mean annual precipitation (WorldClim V2)	919 mm yr^{-1}, unimodal	874 mm yr^{-1}, unimodal	727 mm yr^{-1}, unimodal	738 mm yr^{-1}, unimodal
Mean annual temperature (WorldClim V2)	28.0°C	28.2°C	28.4°C	28.3°C
Population density 2015 (Gridded Population of the World V4)	95 persons per km^2	95 persons per km^2	197 persons per km^2	129 persons per km^2
Nearest market town	Zebilla, 16.6 km	Zebilla, 6.7 km	Garango, 5.9 km	Tenkodogo, 20.5 km

	Site name (alternative name)			
Characteristic	**Binaba (Asam)**	**Tanga (Tangabote)**	**Bidiga (Bedega)**	**Ladwenda (Lagdwenda)**
Reservoir construction date	1969, rehabilitated 1995 and 2015	1994	1970, rehabilitated 1989	2002
Maximum reservoir size (Jones et al. 2017)	38.0 ha (0.890 Mm^3), perennial	11.7 ha (0.164 Mm^3), ephemeral	61.3 ha (1.769 Mm^3), perennial	42.1 ha (1.031 Mm^3), perennial

1.4.2. Climate

While the southern half of the Volta basin is located in the humid tropics, the northern half is situated in semi-arid drylands[1]. Mean annual precipitation ranges from 1700 mm yr^{-1} in parts of Ghana to less than 400 mm yr^{-1} near the Malian-Burkinabé border, averaging 965 mm yr^{-1} based on WorldClim 1970-2000 data (Fick and Hijmans, 2017). Most precipitation falls when the Inter-Tropical Convergence Zone is at its northerly extent, between May and September, with peak rainfall occurring in August (Figure 4). This 3-5 month period represents the only rainfall and main cropping season for most of the basin, except for areas near the Ghanaian coastline where total rainfall is higher and bi-modal.

Mean monthly temperatures across the basin range from 25.5 °C in August to 30.5 °C in April, averaging 27.6 °C (Figure 4). Climate change is expected to increase mean annual temperatures by approximately 2.7°C and mean annual precipitation by 80 mm yr^{-1} by 2050 compared to 1950-2000 averages, based on the IPCC A2a emission scenario (differentiated world, high population growth, high carbon emissions), although there is a high level of uncertainty associated with these estimates and impacts will be locally variable across the basin (Mulligan et al., 2011).

[1] Using the Kopper-Gieger climate classification system

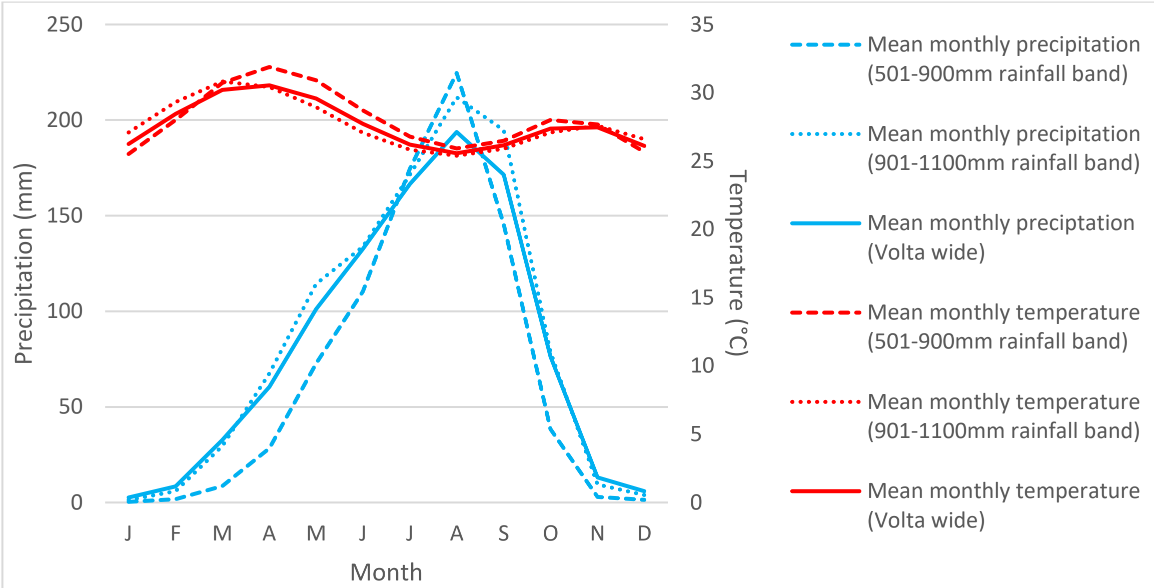

Figure 4: Mean monthly precipitation and temperature across case study site rainfall bands and across the Volta basin, based on interpolations of observed data from 1970-2000. Source: World Clim V2.0 (Fick and Hijmans, 2017).

1.4.3. Socio-economics

Rates of poverty in the Volta basin are some of the highest in the world. The Human Development Index is a composite indicator of human development based on measures of life expectancy, education and living standards, computed and reported annually by the United Nations. Ghana was classified as medium on the Human Development Index in the most recent report, ranking 139 out of 188 counties, while all other basin countries were classified as low with Burkina Faso ranking fourth from the bottom at 185 (UNDP, 2016). All six are food deficit countries, meaning food consumption falls below what is required to meet recommended per capita calorific intake (UNDP 2016). Gross per capita annual income ranges from $1,262 in Togo to $3,839 in Ghana, and between 11% and 64% of the Volta basin population are estimated to live in severe poverty using the UN's multidimensional poverty index (see Table 2).

Table 2: Volta basin country profiles. Sources: United Nations Statistics Division (2016) - % employed in agriculture; United Nations Development Programme (2016) – all other data.

Country	Population in 2015, millions (average annual growth rate 2010-2015,%)	Human Development Index Rank in 2016	Gross national income per capita in 2015 (USD)	Population in severe multidimensional poverty in 2015 (%)	Active population employed in the agricultural sector (%)[2]
Benin	10.9 (2.7)	167	1,979	38	-
Burkina Faso	18.1 (2.9)	185	1,537	64	85
Cote d'Ivoire	22.7 (2.4)	171	3,163	32	-
Ghana	27.4 (2.4)	139	3,839	11	42
Mali	17.6 (3.0)	175	2,218	56	66
Togo	7.3 (2.7)	166	1,262	23	54

Population in the Volta basin is increasing rapidly at 2.7% per annum on average across the six countries. International and seasonal migration impact on population dynamics and labour availability in the region, including for agricultural work. Migrants to Ghana arrive from all other countries in the Volta basin as well as Nigeria and Niger (IMO, 2009). In general, there is a north-south migration trend across the Volta basin with dry season migration of seasonal workers (particularly youth) and Fulani cattle herders from more to less arid climates, although it is difficult to say how important this is for population dynamics because seasonal migration figures are not documented (IMO, 2009).

1.4.4. Environment

Vegetation across the Volta basin ranges from moist semi-deciduous forest in the south, to mixed-length grasses interspersed with deciduous trees in the middle, and short grasses and short drought-resistant deciduous trees characterising the northern savannas (Boubacar et al., 2005). Vegetation clearance, declining soil fertility and soil erosion threaten land quality and biodiversity in Burkina Faso (Douxchamps et al., 2014), while

[2] Most recent data reported, which were from 2005 except for Ghana where data from 2010 were available. No data were available for Benin or Cote d'Ivoire.

infertile soils, dry spells and drought impact on land productivity across the Volta basin (Lemoalle and de Condappa, 2010).

1.4.5. Agriculture and irrigation

Depending on the country, between 30% and 70% of land resources are classified as agricultural in the Volta basin, comprising arable (temporary crops and fallow land), permanent cropland and pasture (FAOSTAT, 2016). More than half of the agricultural land in Benin, Burkina Faso and Togo is temporarily or permanently cropped, while the inverse is true in Cote d'Ivoire, Ghana and Mali where agricultural land is dominated by pasture. Less than 1% of this agricultural land is equipped for full or partial irrigation based on official records (see Table 3).

Table 3: Agricultural land distribution across the six Volta basin countries. Source: 2013 data in FAOSTAT (2016).

Country	Agricultural land in 1000's hectares (% of total land area)	Arable land in 1000s of hectares (% of agricultural land area)	Permanent crops in 1000s of hectares (% of agricultural land area)	Land equipped for irrigation in 1000's of hectares (% of agricultural land area)
Benin	3,750 (33%)	2,700 (72%)	500 (13%)	23 (0.6%)
Burkina Faso	12,300 (45%)	6,200 (50%)	100 (1%)	55 (0.5%)
Cote d'Ivoire	20,600 (65%)	2,900 (14%)	4,500 (22%)	73 (0.4%)
Ghana	15,700 (70%)	4,700 (30%)	2,700 (17%)	34 (0.2%)
Mali	41,201 (34%)	6,411 (16%)	150 (<1%)	380 (0.9%)
Togo	3,820 (70%)	2,650 (69%)	179 (4%)	7 (0.2)%

Low or variable rainfall and unproductive soils makes this is a challenging agricultural context for much of the Volta basin. Yet agriculture employs more people than any other sector for five of the six Volta basin countries (all except Burkina Faso, where industry and services employ more people). Specifically, agriculture accounts for an estimated 43% of employed people in Benin, 28% in Burkina Faso, 48% in Côte d'Ivoire, 41% in Ghana, 58% in Mali and 38% in Togo, or 43% on average (ILO, 2017).

Lemoalle and De Condappa (2009) divide the basin into four agro-ecological zones distinguished by annual rainfall: the Sahelian zone, with < 500 mm yr^{-1}; Sahelo-

Sudanian, with 500-900 mm yr^{-1}; Sudanian, with 900-1100 mm yr^{-1}, and; the Guinean zone with > 1100 mm yr^{-1} (see Figure 3). Lemoalle and De Condappa (2009) estimate the probability of crop failure to be 53%, 24%, 17% and 8% respectively across these zones, although these figures are based on modelled drought risk and not empirical data. The four case study sites in this thesis are located in the Sahelo-Sudanian and Sudanian zones, where the dominant food crops are millet, sorghum, and maize, while cash crops include cotton and groundnuts (Lemoalle and de Condappa, 2010), rice and market vegetables (e.g. tomatoes, onions, aubergine, chilli) (Boubacar et al., 2005). Further south, cocoa, plantain, palm oil and cashew nuts are the dominant cash crops. Soils across the Volta basin are typically alluvial Fluvisols or eroded and shallow Leptosols (Boubacar et al., 2005) and considered to have low fertility due to low water-holding capacities and climate-induced leaching (Lemoalle and de Condappa, 2010). Cropping practices include crop-fallow shifting cultivation, permanent intensive (no fallow) cultivation common around homesteads and in irrigation schemes, and mixed crop-livestock systems, typically on 1-2 ha farms (Boubacar *et al*., 2005). Access to cultivable land is obtained through inheritance or gifts between family members, through purchase, rental, or by share cropping where part of the harvest or income is shared with the land owner, while farming activities are generally carried out manually or with animal power; use of tractors and other farm machinery is still relatively rare (Boubacar et al., 2005).

Roots, tubers, and cereals constitute over 60% of annual crop production across the six Volta basin countries (Figure 5). Production of roots and tubers is dominated by cassava and yam while maize, paddy rice, sorghum and millet represent the main cereal crops. Spatially explicit sub-national data are available from global or regional cropland datasets, or directly from national governments collated at sub-national levels. Data from the Ministry of Food and Agriculture (MoFA) in Ghana has information on production and harvest area for 22 crops at the district level, while the Ministrie de l'Agriculture (MAHASA)

in Burkina Faso provides the same information for 15 crops, where 2012 is the most recent year with data from both countries. Paddy rice and maize are the only crops which are listed as irrigated in 2012 production data from Burkina Faso, while there is no information on irrigated crop production in data from Ghana. The data from Burkina Faso suggest irrigated production of rice is particularly important; 156,047 tonnes of irrigated rice were produced in 2012, constituting about half of the country's rice production (319,390 tonnes), while 18,951 tonnes of irrigated maize were produced, comprising a small portion of the 156 million tonne annual total. Micro-studies at dams in both Ghana and Burkina Faso all report paddy rice as the main crop grown in planned irrigation schemes, while a range of vegetables tend to be grown alongside this rice and in upstream fields (de Fraiture et al., 2014; Ofosu et al., 2010; Poussin et al., 2015). Poussin et al. (2015) found that irrigated crop diversity varies with season; rice dominates the planned irrigation scheme during the rainy season, while rice, maize and vegetables are grown during the dry season. Lemoalle and de Condappa (2010) estimate irrigation represents <0.5% of the total cultivated area in the Volta basin, and meets less than a quarter of the basin's irrigation potential.

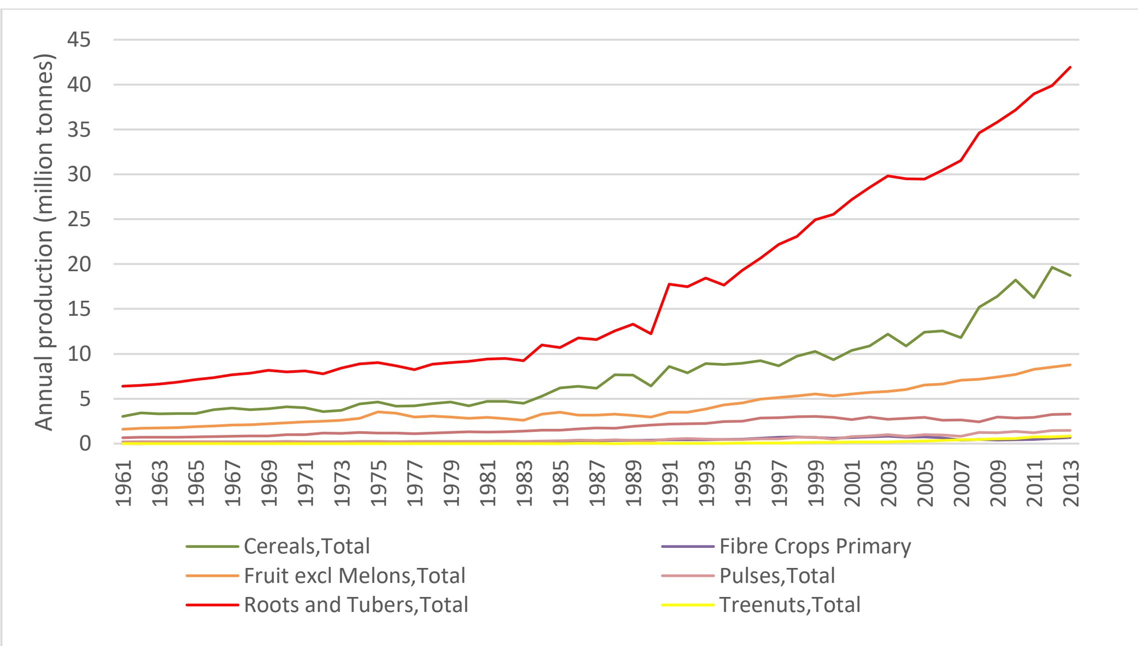

Figure 5: Total annual production across the six Volta basin countries per crop group, 1961-2013. Based on annual data from FAOSTAT (2016).

While total crop production increased by over 530% between 1961 and 2013 across the six countries, from 1.2 to 7.5 million tonnes per year with regional variations, rapid population increases during the same period mean that this translates to a 58% increase in per capita crop production overall, and a decline in per capita production in two countries, Côte d'Ivoire and Togo. Meeting the food requirements of the expanding Volta basin population will require an increase in production across many food groups (KC et al., 2018), to avoid diet-related health problems (Tilman and Clark, 2014) or over-reliance on food imports (Miguel A. Altieri et al., 2012). Future increases in food production will be achieved in the context of the *Comprehensive African Agriculture Development Programme (CAADP)*, to which each of the Volta basin countries have each signed up with varying commitments. Under the CAADP, Burkina Faso commits to promoting investments in sustainable land and water management and sustainable agricultural development. Ghana takes a different approach, committing to investing in irrigation to reduce rainfall dependencies, and to promoting selected commodities for increased food security.

All six countries have also signed the Declaration de Dakar, under the Economic Community of West African States, where members pledge to increase the irrigated area in Sahel countries from an estimated 400,000 hectares in 2013 to 1,000,000 hectares by 2020. In addition, both Ghana and Burkina Faso (and Tanzania and Ethiopia) are participating in the *G8 New Alliance for Food Security and Nutrition*, which requires that, in exchange for funding from G8 countries and companies such as Monsanto, Yara, and Syngenta, governments alter their seed and land tenure laws to protect investors. It is early days to assess the implications of this, but highlights that land tenure is a critical variable in land use decisions and will become even more so in the future.

1.5. Analytical approach

This section explains the analytical frameworks applied to the research presented in subsequent chapters.

1.5.1. Science for action

This thesis seeks to contribute to research for sustainable development, a body of science which aims to support societal change by tackling real-world sustainability challenges (Wuelser and Pohl, 2016). Many authors argue that scientific input is essential for effective design of sustainability policies because of the complexity of sustainability problems (Cash et al., 2003; Collier et al., 2011; Gusmão Caiado et al., 2018). Delivering science that helps solve sustainability problems may involve interdisciplinary (Gallopín et al., 2001) and transdisciplinary work (Bennett et al., 2015; Fischer et al., 2007), multivariable, cross-scale studies (Ostrom, 2007), and coproduction of knowledge (Reyers et al., 2015). Above all it requires asking the right research questions (Wuelser and Pohl, 2016). Yet even when science responds directly to a real-world problem, production of scientific knowledge does not necessarily lead to science-led sustainability policy decisions for cultural, practical, political and economic reasons (Gusmão Caiado et al., 2018). Scientists do not always have the knowledge or tools to provide policymakers with timely, evidence-based advice of how to design and manage an intervention for sustainable outcomes. Non-scientific knowledge sources, including personal experience, beliefs and unsubstantiated or biased claims are frequently used to inform environmental policy irrespective of the strength of scientific evidence (Barnard et al., 2017), e.g. President of the USA, Donald Trump claimed that the lack of evidence for climate change along with expected economic losses in the domestic fossil fuel industry justified his withdrawal from the Paris agreement, despite overwhelming scientific evidence of climate change and studies showing clean energy is increasingly profitable (Zhang et al., 2017). Lobbyists can also have a powerful influence, swaying environmental and social sustainability policies in

spite of public and scientific opinion, e.g. agrochemical companies successfully prevented the EU from banning glyphosate use (for now)[3], despite mounting evidence of its serious health and environmental impacts (Nicolopoulou-Stamati et al., 2016). Meanwhile at the local level, farmer and other private or shared land owner decision making is inherently complex, dependent on factors such as past experience, personal preferences and objectives, and the enabling environment (Steg and Vlek, 2009; Swinton et al., 2015; Willock et al., 1999). The multiple factors influencing policy and land management decisions raises the question of how useful scientific research can be for mobilising environmental and socially sustainable change. Sustainability problems are by nature complex and while science alone cannot solve these 'wicked' problems (e.g. trial and error, willingness and luck are also needed), science can help identify the solution space. A scientific approach to documenting information and to make inherent biases, assumptions and limitations explicit can provide insights that are missed or lack credibility from other sources. Scientific methods for knowledge generation are widely respected making science a powerful knowledge source that can empower or challenge politicians and lobbyists to back up their claims, and encourage evidence-based decision-making at all levels.

A preference for science that supports societal change influenced my choice of methods. For example, in Chapter 5 I used a social valuation approach to study the value of ES as perceived by farmers. Such approaches are able to incorporate multiple worldviews into the analysis and thus obtain results that are more likely to have "societal rather than (only) academic impact" (Jacobs et al., 2016). Social valuation is also considered more appropriate for societies less familiar with or able to participate in monetary transactions, such as subsistence and low-income societies (Folkersen, 2018).

Research for sustainable development can and should also contribute to closing

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[3] For further details, see http://www.pan-uk.org/glyphosate-victory-corporate-lobbying-not-science/.

academic knowledge gaps. In tackling real-world problems, the research contributes to building an evidence base showing which scientific theories and approaches are applicable in different contexts. This helps test existing theories, close broader knowledge gaps and stimulate new theory development (Eden and Ackermann, 2018). For example, in Chapter 2, four common methods for surface water detection were tested in the Volta basin context, which showed none of these methods when applied to Landsat satellite imagery were able to reliably detect very small reservoirs (< 3 ha) irrespective of climate or water greenness, therefore mixed method approaches are needed.

Finally, this research was part-funded by the CGIAR Water, Land and Ecosystems research programme, through a project on ‘Targeting agricultural innovations and ecosystem services in the northern Volta basin’ (TAI) (2015-16), and through Bioversity International centre funding. The CGIAR is a food system research network with a global reach to farmers and policymakers, while Bioversity International is an international research for development organization within the CGIAR, focused on safeguarding and using agricultural biodiversity to attain more sustainable food systems. The thesis research aligns with the TAI project agenda and thus addresses a CGIAR Water, Land and Ecosystems research priority. The hope is that supporting the CGIAR’s research agenda will increase the likelihood that research in this thesis will be put to practical use.

1.5.2. Multi-level

Research for this thesis applied quantitative methods over large spatial extents (the Volta basin, ~400,000 km^2) and qualitative approaches in four case study landscapes 32-109 km^2). Conducting research at nested spatial extents is appropriate in ES science (Geertsema et al., 2016) because of the spatial and temporal lag between cause (“ecosystem function”) and effect (“ecosystem service”) (Fremier et al., 2013). Multi-level approaches can be useful for validating findings at larger scales and scaling up local studies (Scholes et al., 2013). They can also stimulate cooperation between social actors,

by highlighting priorities, dependencies and values that are shared across places and institutional levels (Barnaud et al., 2018).

1.5.3. Mixed methods

To design the study and interpret findings, I used remote sensing, statistical, and social science methods drawing on knowledge from water resource, food system, ecosystem service, and development disciplines. For example, I used methods from physical sciences, such as classification of remotely sensed images in Chapters 2 and 3, and methods from social science, including focus groups and thematic data analysis in Chapter 5. Both deductive and inductive reasoning were used to analyse and interpret data. For example, Chapter 2 on reservoir mapping takes a deductive approach that used prior evidence that surface water can be mapped remotely and compares classification techniques to identify the optimal approach in the Volta basin. In contrast, Chapter 5 used inductive reasoning to analyse responses to open-ended questions about ES supplies and value judgements, to develop new interpretations about how perceptions of where a service exists and its value differ between individuals.

There are advantages and drawbacks of this mixed method and multi-disciplinary approach. Applying knowledge and methods from a single field makes it easier to develop specialist expertise and a deeper knowledge base to contribute to theoretical advances in that subject. Integrating approaches from several disciplines means developing a much broader set of skills and learning how to interpret and integrate research methodologies and findings which are communicated based on different language (jargon, phrase formulation), conventions and epistemologies (Bracken and Oughton, 2006). Yet tackling real-world sustainability problems requires collaborative, iterative and transdisciplinary approaches to research and decision-making (Opdam et al., 2013), where research draws on knowledge and approaches from multiple disciplines (Liu et al., 2015). Schwartz et al. (2017) goes so far as to argue that developing transdisciplinary knowledge and skills is a

"cooperative responsibility" for scientists committed to solving practical environmental problems.

Geographers in particular have an opportunity to bridge disciplines as the subject itself combines human and physical sciences (Bracken and Oughton, 2006). Geographers with skills in both of these disciplines can help bridge the gap and facilitate communication within interdisciplinary teams capable of tackling big sustainability questions. To tailor courses and help geographers develop this skillset, perhaps there is scope for mainstreaming a third category of geographer alongside the human and physical: the systems geographer.

I have personally found it both challenging and rewarding to improve my knowledge in multiple fields, primarily water resource, agricultural planning, ecosystem service and sustainability sectors. The challenge has been to gain enough depth and breadth of expertise to understand concepts, design and conduct robust research in both physical and social sciences. A key advantage is that this has helped me to better contextualise and show the relevance of my results across disciplines. For example, in Chapter 2 I felt it was important to go beyond the standard approach to reporting remote sensing results - showing the reliability of water detection from an image classification perspective - to also assess the relevance of the outputs within the agricultural policy context. I have attempted to introduce terminology and concepts using clear language throughout this research as a way of making this text accessible across disciplines.

1.5.4. Participatory approaches

Co-production of knowledge with non-academic stakeholders substantially improves the relevance of research for real-world problems (Wuelser and Pohl, 2016). Scientists or other individuals who are "outsiders" to a community can miss fundamental information that local actors are aware of and which help answer a research question. Local

farmer knowledge of complex socio-ecological contexts, histories and trajectories can provide insights that help envisage what a sustainable agricultural landscape may look like (Feldman and Welsh, 2010; Kloppenburg, 1991).

Participatory research where local stakeholders actively shape knowledge generation is therefore particularly appropriate for research for sustainable development projects, and is used in chapters 4 and 5 of this thesis. Chapter 4 draws on focus groups and key stakeholder interviews to identify potential factors influencing irrigation adoption, while Chapter 5 used participatory ecosystem service mapping along with focus groups and individual interviews for co-production of knowledge regarding ES and HWB outcomes. Geertsema et al. (2016) argue that positive behaviour change and more informed field, farm and landscape level planning is encouraged by enabling local stakeholders to identify, prioritise and map the spatial distribution of ES. Participatory methods can empower farmers and other non-scientists and encourage knowledge sharing and joint learning (Reed, 2008).

However, power asymmetries need to be carefully managed in participatory research (Barnaud and van Paassen, 2013). The use of focus groups in particular is not always encouraged because these are subject to group power dynamics, which can inhibit individuals from expressing their full opinion, and discussions are influenced by the facilitation approach (Powell and Single, 1996). Yet focus groups are time-effective and useful for gathering initial knowledge baseline and spectrum of perceptions of the priority issues on complex topics (Powell and Single, 1996). Some people feel more comfortable sharing their opinions in a group setting rather than one-on-one with an interviewer (Denzin and Lincoln, 2000). Ayrton (2018) argues that power relations within the focus group are not necessarily a disadvantage because they can provide useful insights into the population power dynamics.

For focus group work in this thesis, following Slocum et al. (1995), I concentrated

on giving ownership of each task to focus group participants and creating a neutral space where all perspectives are acknowledged as valid, e.g. including all viewpoints when summarising the discussions to the group during facilitation. As part of this, women and men were separated by focus group to minimise the influence of gender power dynamics on the discussions. I complemented focus groups with individual semi-structured interviews to distil in-depth information on subjective opinions, values and knowledge. I conducted interviews in public places that should be considered neutral to participants, such as unused school classrooms and village centres, important for helping the interviewee feel comfortable (Longhurst, 2009). The depth of information obtained through these interviews went well beyond that obtained through the focus groups, e.g. interview responses revealed that participant values for ecosystem services were cast along socio-economic lines. In general, participants appeared to enjoy the opportunity to give their individual opinions and appeared unreserved in their responses. A key disadvantage was that each interview for Chapter 5 took between 1 and 1.5 hrs making this approach time-consuming and tiring for the interviewer and translator. To deal with this, I limited the interviews to four per day for each translator. However this meant that the total number of farmers interviewed was relatively low (n=37 across four study sites).

1.5.5. Ecosystem service approaches

Since its emergence, the concept of ES has created some controversy and confusion among scientists (Fisher et al., 2009; Norgaard, 2010; Wallace, 2007). Some conservationists consider the notion of ES too anthropocentric, arguing it reinforces the view that human needs trump all others, and non-human species and their habitats are not worth conserving for their own sake (Ingram et al., 2012; McCauley, 2006). Others argue biodiversity loss impacts on the ecological functions that underpin ES and therefore biodiversity conservation can go hand in hand with ecosystem service conservation (Díaz et al., 2006; Harrison et al., 2014; Turner et al., 2007) and improve conservation efforts

both within and outside of protected areas (Armsworth et al., 2007; Ingram et al., 2012). However the evidence linking biodiversity to ES remains patchy (Cardinale et al., 2012) and the relationship is not always positive (O'Connor and Crowe, 2005). In my view, the concept of ecosystem service is an effective means of conveying how dependent we are as humans on nature and ecological processes for our well-being, and why we should care about the condition and functioning of the ecosystems in which we live. It should be used to complement not replace moral reasons for nature conservation. Efforts to conserve biodiversity will always require prioritisation: it is not possible to conserve all biodiversity everywhere (Thompson, 2010). ES provide a method for organizing and prioritising conservation efforts based on recognisable human needs, which is arguably more likely to gain traction with a critical mass of people than arguments based on the intrinsic value of biodiversity.

Ecosystem service approaches "seek to measure and map the services and to make their relative changes comparable by valuation" (Primmer & Furman 2012, p.88), with the end goal of generating information that land managers can use to inform decision-making (Carpenter et al., 2009; Cowling et al., 2008; Primmer and Furman, 2012; Ruckelshaus et al., 2013). This can include analyzing trade-offs between service production in specific locations, or identifying synergies between outcomes of ecosystem service change for different beneficiary groups or for conservation and social goals (Ruckelshaus et al., 2015). Ideally a full range of ES should be measured and interactions between services and their uses taken into account (Carpenter et al., 2009), although in practice this is rarely feasible due to the number and complexity of potential interactions (Primmer and Furman, 2012).

The value of ES for people can be measured using monetary approaches including based on market prices, revealed and stated preferences, and benefit transfer (Costanza et al., 2014; de Groot et al., 2012). Monetary approaches have been widely

applied and have the advantage that they allow for measures to be easily compared across contexts. Yet many researchers have called attention to the short-comings of measuring the value of ecosystems in economic terms, calling for inclusion of social, place-based and biophysical values into ecosystem service valuations (Brown, 2013; Carpenter et al., 2009; Christie et al., 2008; Cowling et al., 2008; Kumar and Kumar, 2008; Sherrouse et al., 2011). A key challenge is that values are plural, meaning the type of value that individuals assign to nature can vary across and within groups (Kenter et al., 2015). Individuals may perceive an ES as important for its economic value (monetary benefits), instrumental value (the contribution it makes to an individual's wellbeing), intrinsic value (irrespective of its benefits on humans) or relational value (the way an individual relates to the service) (Small et al., 2017). While monetary approaches to ES valuation do not exclude the possibility that higher values are assigned to ES with, for example, higher instrumental or intrinsic values, they encourage the value of ES to be assessed in solely economic terms. Another challenge is that monetary valuation approaches are not well-suited to mainly subsistence societies. Market-based approaches are inadequate where many ES have no local market price, while stated preference methods, such as contingency valuation (e.g. willingness to pay) or choice modelling, are inappropriate where people are not accustomed to dealing with money (Christie et al., 2012). Where people have difficultly assigning monetary values to services that are not usually priced, this may result in inconsistent or invalid responses (Ludwig, 2000).

Multiple alternatives to monetary valuation have been explored. These include identifying socio-culturally assigned values (Bryan et al., 2010; Iniesta-Arandia et al., 2014; Raymond et al., 2009; Scholte et al., 2015), quantifying ecosystem service contributions to specific HWB outcomes (Olander et al., 2017) and quantifying their relative importance for enabling progress towards the Sustainable Development Goals (Wood et al., 2018). These pluralistic values are generally collected using questionnaires, interviews and/or

participatory methods, providing detailed information about motivations for individual value judgements. They are therefore a useful complement or alternative to monetary valuation techniques (Christie et al., 2012).

Chapter 5 of this thesis applied an ecosystem service approach that sought to take into account the full range of services perceived by local stakeholders and quantify their values using a non-monetary approach. Following Daw et al. (2011), values for these services were disaggregated to the individual level.

1.5.6. Open science

Scientific research outputs should be accessible to everyone. Science is largely funded with public money and, in the case of research for (sustainable) development, is designed to help solve real-world problems. Knowledge is power and the use of knowledge is political (Escobar, 1995). Preventing the public and certain groups of scientists from accessing scientific knowledge disadvantages these groups and hampers scientific and real-world progress. The long-standing embargo on the vast majority of scientific research, in the form of journal charges and copyright claims, handicaps researchers from developing countries from competing scientifically (Collins, 2005) and makes it even harder for policymakers worldwide to use science to inform their decisions.

Similarly, fast and robust data collection and processing tools can be expensive and only accessible to well-funded research teams. This creates an uneven playing field for global scientists and makes it harder for next users to re-apply methods in new contexts, hindering knowledge generation. In particular, environmental and social data can be hard to access or to validate at scale in rural settings globally (Selomane et al., 2015) and especially in parts of Africa (Barnard et al., 2017; Stephenson et al., 2017), because of physical constraints (poor roads, security issues, high cloud cover on satellite imagery during humid periods, lack of laboratories for biophysical data processing), administrative

data limitations (lack of postal or telephone address records, lack of maps documenting admin boundaries, land holdings or uses) and communication barriers (diversity of languages demanding multiple translators, high level of illiteracy). Yet monitoring environmental and social components of a system is a first step to managing socio-ecological systems for sustainable development (Selomane et al., 2015).

For these reasons, I used open access data (e.g. Landsat satellite imagery, free global datasets on land use and climate among others) and low-cost or open access tools (e.g. Google Earth Engine, R, WaterWorld) to conduct research for this thesis, and sought to make outputs openly accessible. However, I used the proprietary software NVivo for qualitative data analysis in Chapter 5, because I was unable to find an open access tool with equivalent capabilities, highlighting a gap in the open tools domain. Chapter 2 of this thesis has been published in an open access journal (Jones et al., 2017) and subsequent publications will similarly be made open access if feasible, but the cost of open access publishing remains prohibitive. This barrier may soon be lifted with the notable increase over the last decade in open access journals or journals offering open access (Dodds, 2018), including new journals such as PeerJ[4] that have low subscription fees, allow pre-prints, have an open review process and give full copyright to authors.

[4] https://peerj.com/

1.6. Research process

Research outcomes are shaped by the positionality of the researcher and the research subject in a given context, and how a researcher addresses potential biases that may arise (Attia and Edge, 2017). Reflecting on these issues elucidates the role of power relations, culture, beliefs and environment in shaping the research approach and findings, embracing research as a “process and not just a product” (England, 1994, p.244). In the following sections, I critically analyse the effect of the research context and my position as a female, European researcher on the implementation of my selected methodologies for collecting primary data for Chapters 3, 4 and 5, and discuss how challenges were overcome. These data were collected at case study sites in Burkina Faso and Ghana, through interviews, questionnaires, focus groups, transect walks and land use surveys.

1.6.1. Lost in translation

Conducting primary research through a translator is often inevitable in cross-cultural studies because of language barriers. The four case study sites in this thesis each have several commonly spoken local languages, corresponding to diverse local ethnic groups. As such, I had four different research assistants translating in the focus groups and face to face surveys, and we asked participants to answer only in the dominant local language (which all participants spoke) so that the translator could understand.

The translation process had several implications. Each translator had their own instinct about the best way to communicate the questions to be sensitive and clear and to translate the responses, and on occasions I asked the questions myself (when people spoke English or French), meaning there were five different interpretations in play. Interpretations of language are central to the exchange between interviewer and interviewee, and ensuring consistency in interpretations underpins the validity of qualitative studies (van Nes et al., 2010). I limited potential inconsistencies by impressing on each person the importance of translating things as directly as possible. Before starting I worked

through each question with the interviewer to make sure we had a shared understanding of the interview questions. I quickly realised the skill of the translator was critical – first in having a high level of skill in each language; second in having strong interpersonal skills to be able to connect with the participant and with me, as emphasised by Longhurst (2009); third in being patient and having good concentration levels so as to consistently translate everything. I had three translators with all of these skills, while at the fourth site the lower skill level was reflected in the more limited breadth and depth of information gathered. I was careful to take this into account when analyzing the data, and cross-checked any potential findings with focus group data and my personal observations where possible.

In general, I found it limiting not to be able to understand directly what a participant was saying and thus be able to filter out the influence of the translator's own interpretation. I wanted to understand the detail, the nuances, that are lost in translation, and also to be able to communicate and build a rapport directly with each person that was kindly giving me their time and speaking earnestly, sometimes passionately, about issues I wanted to know more about. However a key advantage was that the translators were able to use a style of language and expression that the interviewee readily understood which helped with the interview flow and to put the interviewee at ease. Post interview I discussed with the translator the responses I had noted to make sure I had understood correctly.

1.6.2. Ethical issues

In my case study sites, outsiders and particularly Europeans are sometimes perceived and approached as potential sources of gifts, money, and investments in the community. This can lead to false expectations of the benefits of participation in research studies. I made sure that at the start of any work with human subjects I took time to explain the research purpose; that participation was voluntary and unpaid, and; this was not a development project and therefore would not necessarily lead to any changes in the community. After this introduction and before any research activities began, each

participant was asked to give their signed consent to participate or to feel free to leave if they preferred not to participate.

However, the problem of not giving incentives that could bias participation, but compensating people adequately for giving up their time to participate, is challenging in poverty contexts where people do not have spare resources to cover the direct or hidden costs of participation. The ethical conditions of this study required that research with human subjects depended on participant kindness towards strangers and willingness to give up their time to participate in research for a minimal non-monetary incentive, i.e. a free, hot lunch and small practical gift (soap or rice). In the field, I felt this incentive was inadequate compensation for each farmer’s time especially given their resource constraints. Asking farmers not to work for a day impacts on farm productivity with associated costs to food availability and income, with potentially significant consequences. In academic circles, some argue that monetary payment may lead to vulnerable persons agreeing to participate despite risks that they may incur, and that payment will bias the sample (Dickert et al., 2002). Others suggest that the fear around monetary incentives to participation is unsupported by evidence and should be considered equal to other non-monetary incentives (Largent and Fernandez Lynch, 2017).

Research on the effects of incentives on participation, including in poverty contexts, is dominated by medical studies. Local perspectives on compensation for biomedical research in rural Zimbabwe showed that 90% of people interviewed expected reasonable compensation for participation with a preference for individual monetary rewards, but that local perspectives on compensation are rarely considered by ethics committees or at the research design stage (Mduluza et al., 2013). No research appears to have been done to check local views on reasonable compensation for participation in qualitative social science research in poverty contexts. More attention needs to be given by academics and ethics review committees to what is, and what participants consider, fair

compensation in social research studies in these contexts, and provide evidence justifying the preference for minimal incentives. Based on the experience of conducting social surveys for this thesis, I will give more thought to how to provide appropriate compensation in future. For example, I would seek ethical approval to give people payment in exchange for participation or to give a substantial, practical gift, such as mosquito nets, school books, farm tools or seeds, selected with community input.

1.6.3. Use of gatekeepers

Cultural norms, a lack of readily available data on local household composition, and the absence of existing relationships with communities at my case study sites, meant that I requested the assistance of village chiefs and local farmer representatives to engage farmers in my research. This required significant time investment, as is commonly the case in social research where the researcher is considered an outsider by those people who are accepted inside the community (Sanghera and Thapar-Björkert, 2008). Specifically, two levels of gatekeepers needed to be approached at each case study site in order to gain access to local smallholder farmers. This involved one or two visits to the local village chief, who then provided contact details and permission to talk to a key local farmer representative, i.e. local dam management committee (Tanga), agricultural extension worker (Binaba) or local farmer association leader (Bidiga and Ladwenda). At least one meeting and multiple communications by telephone were held with the farmer representatives, who subsequently contacted local farmers to seek voluntary participants for a one day research activity. While the process of securing farmer participation was lengthy, the gatekeepers were invaluable in providing access to local farmers and I much appreciated their generosity in assisting a relative stranger.

The use of gatekeepers affected the research in this thesis by their influence on who participated in the social surveys, i.e. who was approached, and the manner in which the invitation to participate was conveyed. In particular, I had pre-defined criteria for

participant selection related to age, gender, resident community, and farming practices. While criteria for participant selection were largely met at all sites, including having approximately 50% men and 50% women, a mix of ages, and people from several of the local villages, one criterion was not. Specifically, I asked for about half of the participants to be those that did not have a plot in the irrigation zone, with the rest irrigators, but on completion of the socio-economic profile questionnaire I found very few of the participants fell into the former category. This may have been because the full set of criteria were too challenging to meet, or because the gatekeepers did not have access to many farmers not practicing any irrigation. I dealt with this by adapting my data analysis in Chapter 5 to only consider divisions between groups which had relatively equal sample sizes.

While selection criteria set limits on which farmers can be invited to participate in research, participant selection is likely to be biased by the gatekeeper's personal inclinations, relationships and constraints. For example, gatekeepers in this research may have prioritised friends/family members in case the research proved educational or otherwise useful to participants, or farmers that had a mobile phone and were thus easy to contact to avoid the task taking too long. These types of biases are difficult to avoid when using gatekeepers, and support the idea that the impact of gatekeepers on research requires further theoretical and methodological consideration (Crowhurst and Kennedy-Macfoy, 2013). Gatekeepers are influenced by their relationship with the researcher (Campbell et al., 2010), where a good relationship is more likely to inspire the goodwill of a gatekeeper to facilitate the research. I had a limited amount of time to build strong researcher-gatekeeper relationships prior to commencing the social research, yet gatekeepers were generally friendly, responsive and trusting in their attitude towards me. At the Ghana study sites, their open attitudes may have been influenced by previous research on dam and water resource management conducted by other research teams, helping to foster a positive image of researchers. At all sites, I felt my positive relationships

with gatekeepers and farmer willingness to participate in the research were in part thanks to the local norm of welcoming and assisting strangers, and good advice from my local research assistants that helped ensure I followed cultural norms during my initial discussions and requests.

The relationship between the local farmer representative and individual farmers is also likely to have influenced who gave their consent to participate. For example, during scoping fieldwork at Binaba in April 2016, I perceived that the agricultural extension worker held some degree of authority over local farmers, with farmers quick to defer to the extension worker view on issues of best farming practices or farmer decision making. Farmers who were asked to participate in research for this project may have felt they should accept because of the extension worker’s local authority. Meanwhile at Ladwenda, the leader of the farmer association appeared to be well-liked among local farmers, many of whom stopped to talk to him or greeted him jovially at our initial meetings. His popularity may have encouraged farmers to consent to participate in the research or equally feel comfortable refusing to participate.

1.6.4. Research fatigue

Social survey participants at the Ghana case study sites were noticeably less enthusiastic than at the Burkina Faso sites. I used recommended facilitation techniques to encourage participants to actively engage, including interactive tasks and directed questions to individual participants, which helped. I also ensured focus group participants had regular breaks to keep energy levels up. However, at the Burkina Faso sites, participants were excited and engaged from the moment the focus group discussions began, whilst at the Ghana sites participants arrived looking disinterested and reluctant to provide input. The latter may be simply down to cultural differences, or may be symptomatic of research fatigue, where individuals grow tired of research engagement and are reluctant to engage in ongoing or new research (Clark, 2008). Research on water resource

management and irrigation performance has been conducted by several teams across the Upper East Ghana over the last decade (Birner et al., 2010), including in at least one of our case studies, Binaba (Poussin et al., 2015; Renaudin, 2012). While studies have also occurred in the Centre-Ouest region of Burkina Faso (Fowe et al., 2015; Poussin et al., 2015; Renaudin, 2012), none are reported for Centre-Est where my study sites are situated.

In communities with a history of repeat research activities, people are likely to express research fatigue where these activities do not lead to perceptible changes on the ground (Clark, 2008). This is common even in research where the purpose was not to bring about change (Clark, 2008). Unfortunately implementing real-world change as a consequence of scientific research is challenging in any project (Collier et al., 2011; Liu et al., 2015; Opdam et al., 2013). At Binaba, Poussin et al. (2015) conducted farmer surveys and identified a lack of agricultural inputs and product marketing opportunities as key constraints to improving irrigation performance, and that local authorities were concerned with conserving water resources but not necessarily removing other constraints to irrigation. Therefore even closer engagement of local authorities may not have resulted in the issues raised by farmers being addressed.

The time, cost and organisation required to participate in research can also create research fatigue, especially where voluntary, unpaid participation is requested (Clark, 2008) as is recommended by many qualitative research ethics committees to avoid the potentially unethical problem of paying people to participate (Head, 2009). Fortunately in this research, sufficient numbers of farmers consented to attend the focus group and interview activities with a small non-monetary incentive.

1.6.5. Research as an outsider

I was fortunate to travel to both Burkina Faso and Ghana, for personal reasons

and as part of the TAI project, before starting my thesis research. This gave me a good understanding of the basic cultural norms. However, I had not worked closely with rural villagers.

A degree of trust is important to get research participants to give their honest opinion and open responses in qualitative research (Denzin and Lincoln, 2000). In all the case study sites, my assistants and I were strangers to the participants. While strangers are warmly welcomed as a cultural norm at all study sites, building trust takes time and this was a challenge to do in my relatively short field contact. I dealt with this by, at the start of the focus group or interview work for Chapters 4 and 5, speaking to my translators and assistants about wanting to make participants feel comfortable with us and able to speak freely. I encouraged them to use their own judgement to make this happen and we came up with some ideas to facilitate the process. For example, we made sure the chairs in the workshop were laid out in a circle for group discussions, gave name tags to each participant, and asked each participant to introduce themselves to the group at the start of the day. We started with group activities to get participants warmed up, more familiar with me and with my research assistants, and interested in the research. We tried hard to make each participant feel their opinion was valued by actively asking quieter participants questions to get them engaged, and encouraging more vocal participants to find out if their opinion was shared by the group. We also handed over leadership of group work to participants whenever possible. These tactics seemed to help participants feel at ease and sometimes forget the presence of strangers in their midst. Two of my research assistants were particularly good at creating a positive space, quickly developing a rapport with participants, making them laugh and listening attentively to them talk before and during the interviews and workshops. This was a real asset to the research.

As a foreigner walking around the communities with field equipment (e.g. handheld GPS, cameras, tape measures) during land use surveys for Chapter 3, I was

initially viewed as a novelty factor in the communities but also with distrust, with children crowding around to see me and the same children running or turning shyly away if I tried to speak to them. One method I found effective at breaking down this barrier was inviting both children and adults to handle and help use the equipment and responding openly to any questions. This seemed to dissolve the mystery of the newcomer and unusual tools, and put people at ease. In general, I relied on my research assistants to guide me in making sure I approached new people and situations in a culturally appropriate manner. For example, they explained it is important in Centre-Est Burkina to be closer to the ground than the chief when you greet him, by kneeling or squatting, and it is important to accept a sip of fermented millet or sorghum if offered (fortunately very pleasant). It is important at all sites not to use the left hand for eating food, and it is considered rude to start any conversation without asking about a person's well-being and usually their family's well-being too. Respecting these customs was invaluable to making sure I built positive relationships in the case study communities.

Some cultural norms impacted on the research process. For example, in Bissa culture, it is impolite to hurry someone when talking or not allow everyone to voice their opinion on a topic, making timekeeping very challenging at the focus groups in Bidiga. Across all four study sites, and particularly in Burkina Faso, I observed that male voices are frequently given priority over women's during group discussions. As a white, young, female foreigner, leading the research team, I had the impression that some participants were not sure what to think about me in these traditionally male-dominated societies. This was one advantage of needing a translator for nearly every activity; the translators were all male and local, which meant they were easier for local people to relate and accept as task leaders. Women do not readily talk in mixed group situations, nor is it common that they are asked or volunteer to lead group activities. I experienced several instances where a woman stated their opinion and this was dismissed by her husband or a male peer as

unimportant or wrong. This open suppression of women's views and undermining of women's self-esteem was something I am not familiar with, and I struggled to remain impartial during my interactions with local villagers and my facilitation of focus groups. However, my perceptions that men dominate group discussions may overlook the contributions that women make to group decisions in Burkina Faso (Elias, 2015). I had several in-depth conversations with my local research assistants on the topic of gender, and through this understood that women normally express their opinions to their male family members in private, who can then share these opinions in public and take them into account in decision-making. To explore gendered perceptions, I gathered views on ES from both genders separately during focus group activities in Chapter 5. Interestingly there were no statistical differences in the locations or seasonality male and female groups assigned to ES and ED, nor in the importance except for one service (desirable flooding). This implies that there is overlapping knowledge of and values assigned to ES and ED among men and women, reducing the implications of potentially gendered decision-making regarding ecosystem management in the case study sites.

Overall, I had to concentrate to remember all the cultural rules and interact with participants sensitively. I was conscious that there was a risk I could misinterpret body language or tone of voice because they may be used differently to what I am used to, and because of the time lag between observing an expression or gesture and hearing translated words and emphasis. In the data analysis stage, I therefore chose not to use my interview notes regarding participant expressions and body language, and instead focus directly on what participants had said.

1.7. Thesis structure

Subsequent chapters investigate water and dry season irrigation dynamics in reservoir contexts in the Volta basin and impacts on smallholder farmer well-being. Chapters 2 and 3 develop and employ methods in big data science using globally available

imagery, data and cloud-based tools to assess changes in surface water and irrigated cropping (irrigated cropland presence, location and extent) at reservoirs across the Volta basin. Chapter 4 analyses socio-economic and environmental factors associated with patterns in small and medium sized reservoir irrigated cropland and compares the environmental sustainability of this cropland. Chapter 5 uses participatory methods to identify and map ES, ED and their perceived importance to HWB in the four case study landscapes containing community-managed reservoirs, characterizing trade-offs between outcomes and farmer groups. Chapter 6 synthesizes findings of preceding chapters in relation to the central research question, potential policy implications, and priorities for future research.

2. Big data and multiple methods for mapping small reservoirs

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Identifying geographic distribution and water dynamics of reservoirs is a pre-requisite to studying their impact on smallholder irrigated crop production. Information on Volta basin reservoir locations, volumes and seasonality is poorly documented and time-consuming to collect using ground-based approaches. This chapter develops and tests methods for mapping and monitoring reservoir resources in the Volta basin remotely using Google Earth Pro imagery and Landsat satellite derived surface water maps.

2.1. Abstract

Whether or not reservoirs contain water throughout the dry season is critical to avoiding late season crop failure in seasonally-arid agricultural landscapes. Locations, volumes, and temporal dynamics, particularly of small (<1 Mm^3) reservoirs are poorly documented globally, thus making it difficult to identify geographic and intra-annual gaps in reservoir water availability. Yet, small reservoirs are the most vulnerable to drying out and often service the poorest of farmers. Using the transboundary Volta River Basin (~413,000 sq km) in West Africa as a case study, we present a novel method to map reservoirs and quantify the uncertainty of Landsat derived reservoir area estimates, which can be readily applied anywhere in the globe. We applied our method to compare the accuracy of reservoir areas that are derived from the Global Surface Water Monthly Water History (GSW) dataset to those that are derived when surface water is classified on Landsat 8 OLI imagery using the Normalised Difference Water Index (NDWI), Modified NDWI with band 6 (MNDWI1), and Modified NDWI with band 7 (MNDWI2). We quantified how the areal accuracies of reservoir size estimates vary with the water classification method, reservoir properties, and environmental context, and assessed the options and limitations of using uncertain reservoir area estimates to monitor reservoir dynamics in an agricultural context. Results show that reservoir area estimates that are derived from the GSW data are 19% less accurate for our study site than MNDWI1 derived estimates, for a sample of 272 reservoir extents of 0.09 to 72 ha. The accuracy of Landsat-derived estimates improves with reservoir size and perimeter-area ratio, while accuracy may decline as surface vegetation increases. We show that GSW derived reservoir area estimates can provide an upper limit for current reservoir capacity and seasonal dynamics of larger reservoirs. Data gaps and uncertainties make GSW derived reservoir extents unsuitable for monitoring reservoirs that are smaller than 5.1 ha (holding ~49,759 m^3), which constitute 674 (56%) reservoirs in the Volta basin, or monitoring seasonal fluctuations of most small

reservoirs, limiting its utility for agricultural planning. This study is one of the first to test the utility and limitations of the newly available GSW dataset and provides guidance on the conditions under which this, and other Landsat-based surface water maps, can be reliably used to monitor reservoir resources.

2.2. Introduction

Freshwater scarcity is a major constraint to food production in agricultural regions of the world with variable intra- and inter-annual rainfall patterns and poor water storage infrastructures (Rockström and Falkenmark, 2015). In sub-Saharan Africa, seasonal rainfall fluctuations and shortages cause up to 53% crop failure in smallholder farming systems (Hyman et al., 2008). Monitoring water resource availability in such areas is critical to limit food shortages and the subsequent sometimes far-reaching social, political, and economic implications (Vörösmarty et al., 2005).

Small and large reservoirs are a common development investment to avert or reduce water shortages and boost production in seasonally dry, agriculture-dependent regions (Venot and Krishnan, 2011). Reservoirs capture and store runoff to provide farmers with a source of freshwater during dry spells and annual dry seasons, increasing the viable extent, productivity, and resilience of cropping, fishery, and livestock production systems (Douxchamps et al., 2014). “Small” reservoirs are engineered surface water bodies with a capacity of less than one million m^3 (Mm^3) (ICLD, 2016). Small reservoirs are less expensive to construct than larger ones, and are therefore perceived as low cost, high return development devices (Venot and Krishnan, 2011). Decades of investments to construct small reservoirs remain largely undocumented at the river basin level and above (Downing, 2010; Downing et al., 2006; Sawunyama and Mhizha, 2006; Wisser et al., 2010), making their impact on human well-being or environmental outcomes impossible to accurately assess. Information on reservoir locations, volumes, and seasonality (water presence-absence) can guide policies to allocate and manage reservoir water sustainably

and avert agricultural water and associated food shortages. Access to this information would therefore support donors, governments, and NGOs in efforts to better understand the value of reservoirs and target reservoir investments and maintenance to achieve local to global sustainable development objectives.

Information on small reservoirs is challenging to compile and to keep updated at the national, regional, or global level (Lemoalle and De Condappa, 2009). Ground-based assessments of small reservoir locations, capacities, and seasonal volumes are time-consuming to conduct because of the spatial dispersion of these reservoirs and decentralized decision making regarding reservoir investments and maintenance (Birner et al., 2010). Many previous studies have characterized inland surface water resources using free satellite imagery, such as from Landsat (Du et al., 2014; Feyisa et al., 2014; Mueller et al., 2016; Pekel et al., 2016; Sawaya et al., 2003) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (D'Andrimont and Defourny, 2017; Khandelwal et al., 2016; Klein et al., 2017; Ogilvie et al., 2015; Pekel et al., 2014). Where the spatial and temporal resolution are sufficiently high, remotely sensed imagery provides a practical approach to small water body mapping and monitoring (Liebe et al., 2005; Ogilvie et al., 2016). At the time of writing, the highest resolution, freely available imagery that is collected on an intra-annual timestep over long time scales comes from the Landsat satellite series (Wulder et al., 2016). Instruments on Landsat satellites provide near-complete global coverage of multispectral imagery at 30 m resolution and 16-day time steps, from 1982 to present. Specifically, Landsat 4 Thematic Mapper provides imagery from 1982 to 1993; Landsat 5 Thematic Mapper from 1984 to 2012; Landsat 7 Enhanced Thematic Mapper from 1999 to present; and, Landsat 8 Operational Land Imager (OLI) from February 2013 to present, providing 35 years of almost continuous data (USGS, 2017). Accurately mapping waterbodies from Landsat imagery is a non-trivial task, since water can be misclassified as urban areas, shadows, and other objects with similar spectral signatures, or these non-

water objects can be falsely classified as water (Xu, 2006). Sediment or vegetation in water—particularly common in West Africa (Pekel et al., 2016)—alters the spectral signature of water, while cloud and dust particles in the atmosphere obscure or distort information about where land is water-covered (Jensen, 2007).

Researchers have successfully mapped water body locations and extents from Landsat imagery for several decades through the use of spectral indices (Ji et al., 2009; Liebe et al., 2005; Ogilvie et al., 2016). Spectral indices are created by calculating the difference, ratio, or normalised difference of two multispectral image bands and identifying the threshold that enhances the reflectance of wavelengths for objects of interest, such as water (Jensen, 2007). The most effective index or threshold identified to map water is rarely the same between studies (Ji et al., 2009). More recently, (Pekel et al., 2016) used multi-spectral analysis to classify water and non-water over all of the images in the Landsat database from 1984 to 2015, resulting in pixel-level measures of water occurrence at monthly time steps over the entire globe. Their Global Surface Water Monthly Water History (GSW) dataset represents an attempt to establish a globally applicable method for water detection from Landsat imagery. Uncertainties in GSW and other surface water maps are generally reported in terms of pixel-level classification accuracy (Congalton, 1991) rather than the impact on practical applications. However, the level of uncertainty that is acceptable will depend on the end-use, and knowledge of this uncertainty may help to ensure its effective use in policy (Bradshaw and Borchers, 2000). For example, water managers that unknowingly use incorrect information on where a small reservoir exists or when reservoirs run dry may make decisions on water allocation that have serious consequences for the agricultural sector and farmers who rely on reservoirs for their livelihoods. Intra-annual surface water maps derived from Landsat satellite imagery, and particularly the globally available GSW dataset, may be useful for monitoring spatial and seasonal dynamics of small reservoirs in agricultural landscapes opening up opportunities

for improved global reservoir data, but their accuracy for this end-use is currently untested.

The primary objective of this paper was to compare a range of methods for rapid and low-cost monitoring of reservoirs, and to establish levels of accuracy in reservoir characterization using these methods, as reservoir properties and environmental conditions vary. For this purpose, we developed a new method for mapping reservoir extents rapidly across large spatio-temporal extents using free, globally available datasets and tools. We compare the effect of accuracy, which is the level of uncertainty in reservoir surface area and equivalent volume estimates, on information about temporal and spatial reservoir water availability to highlight where improved accuracies may be important for agricultural applications. Using the Volta Basin in West Africa as a case study, we focus on three specific questions: (i) What is the accuracy of reservoir areal extents digitized manually from high resolution Google Earth imagery compared to those derived computationally from GSW or from commonly used spectral water indices applied to Landsat 8 OLI imagery? (ii) How does the accuracy of Landsat-based reservoir area estimates vary with environmental factors? (iii) What information on reservoir size and seasonality can be reliably determined from the GSW and what cannot? Our study represents the first attempt to test the limits of the GSW dataset for monitoring reservoirs of varied size and across a range of environmental conditions in a West African context. Establishing reliable end-uses for the GSW is particularly important given that this dataset is global, publically available, and easy to use. The global applicability of our approach makes it useful to a wide range of stakeholders interested in surface water resources or low-cost environmental monitoring.

We structure the remainder of the paper as follows. Section 2.3.1 presents the study site. Sections 2.3.2–2.3.3 describe the input remote sensing datasets and processing techniques that were used to identify reservoirs and prepare surface water maps. Section 2.3.4 explains how reservoir extents were extracted, and Section 2.3.5 describes the

validation data used to determine the accuracy of these reservoir extents. Sections 2.3.6–2.3.7 describes the comparison of accuracies and analysis of covariance with environmental factors, while Section 2.3.8 explains how we used the GSW-derived reservoir extent data to illustrate potential policy-relevant applications. Sections 2.4.1–2.4.2 reports the accuracy of reservoir area estimates across water classification methods and how accuracies vary with environmental conditions. Section 2.4.3 presents reservoir volume and seasonality derived from GSW where sufficient data were available over the 1200 Volta basin reservoirs. Section 2.5 critically analyses the results and the proposed approach for reservoir monitoring. In Section 2.6, we conclude by summarising the utility of our approach for agricultural applications and in a broader context.

2.3. Materials and Methods

2.3.1. Study Site

The 413,000 km^2 Volta basin, which drains parts of Benin, Burkina Faso, Cote d'Ivoire, Ghana, Mali, and Togo, has a mean annual precipitation level relatively high when compared to other major global basins at 953 mm/yr (Mulligan et al., 2011). This rainfall is unevenly distributed from north to south and seasonally skewed across the basin, with parts of the south receiving over 1700 mm/yr compared to under 400 mm/yr in the northern extremes (Figure 6) and rain typically falling between May and September in the south and June and September in the north, based on WorldClim data (Fick and Hijmans, 2017). Between 11% (Ghana) and 64% (Burkina Faso), of the population are estimated to live in severe poverty (UNDP, 2016).

The Volta basin is a pertinent region to use as a case study given the absence of consistent information on reservoir locations and functionality between and within the basin's six countries (Venot et al., 2012), and the livelihood dependencies on the water stored in the basin's small reservoirs which open up opportunities for dry season food production and supplemental irrigation to avert losses during dry spells (Douxchamps et

al., 2015). A lack of accessible data make it impossible to robustly monitor the basin's water resources, a problem that is emblematic of Africa's water resources (Vörösmarty et al., 2005). Identifying transferable, practical methods for water resource monitoring in the Volta basin and Africa more generally is important to enable better targeting of interventions to manage water resources under the continent's rapid population growth (Gerland et al., 2014) and shift towards more resource-intensive diets (Godfray and Garnett, 2014).

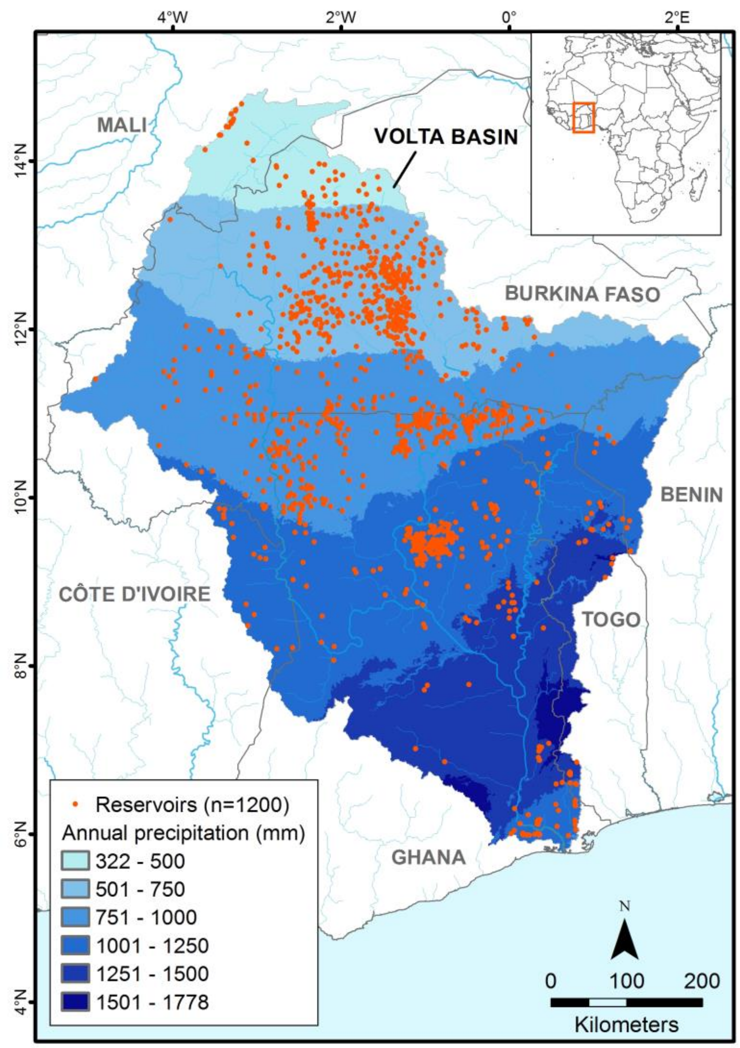


Figure 6: Annual precipitation over the Volta basin study site based on 1980–2010 WorldClim data, with reservoirs identified in this study from Google Earth imagery.

2.3.2. Reservoir Locations

We made use of the most recent imagery hosted in Google Earth in September 2015 and a 100 km × 100 km grid to systematically, manually identify, and map all of the

visible engineered reservoirs across the Volta basin, generating a georeferenced point dataset of existing reservoir locations (). For each of the 1200 identified reservoirs, we placed a point inside the reservoir boundary near the dam wall and where reservoir water was consistently present in months that the reservoir contained water, as shown on imagery within Google Earth's historical imagery collection.

2.3.3. Landsat-Derived Surface Water Maps

We used Google Earth Engine (GEE) to source, generate, and analyse surface water maps that were derived from Landsat imagery. GEE is an online coding environment enabling relatively rapid, server-based analysis of large spatial datasets (Gorelick et al., 2017).

GEE provides access to the EC JRC/Google Monthly Water History V1.0 dataset (Pekel et al., 2016), which contains maps of Global Surface Water created from decadal analysis of Landsat 4, 5, and 7 imagery and contains 30 m × 30 m pixel-level measures of water presence-absence on a monthly time step from March 1984 to October 2015. We worked in GEE to create additional monthly surface water maps from three spectral indices applied to Landsat 8 OLI imagery, for use in subsequent analyses. We sourced 1291 Landsat 8 OLI images that were acquired over the Volta basin (Landsat paths 192 to 197; rows 050 to 056) between 1 May 2013 and 31 October 2015, corresponding to the earliest complete month of data available in GEE and the temporal limit of GSW data. We used imagery that was pre-processed by USGS to surface reflectance and for each image, computed the Normalised Difference Water Index (NDWI) (McFeeters, 1996), Modified NDWI (Xu, 2006) using band 6 (referred to here as MNDWI1), and using band 7 (MNDWI2), indices that are commonly applied in peer-reviewed literature for surface water mapping (Du et al., 2014; Li et al., 2013; Rokni et al., 2014; Singh et al., 2014). The relevant bands in Landsat 8 OLI imagery used to compute the three water indices are:

$$NDWI = \frac{Band\ 3 - Band\ 5}{Band\ 3 + Band\ 5} \qquad (1)$$

$$MNDWI1 = \frac{Band\ 3 - Band\ 6}{Band\ 3 + Band\ 6} \qquad (2)$$

$$MNDWI2 = \frac{Band\ 3 - Band\ 7}{Band\ 3 + Band\ 7} \qquad (3)$$

The OLI on Landsat 8 collects data in slightly different bandwidths to that collected by sensors on earlier Landsat satellites (USGS, 2016). This can lead to substantially different reflectance values (Flood, 2014), and therefore spectral index outputs (Holden and Woodcock, 2016; Li et al., 2014; Roy et al., 2015) between these two sensor groups. Limiting this study to Landsat 8 OLI imagery, rather than including images from several sensors in the Landsat satellite series, allowed for a simpler analysis that ensured consistency in spectral index values over water and non-water features.

We classified pixels on Landsat 8 OLI spectral indices as water, non-water or non-valid (masked), consistent with GSW. Non-valid pixels correspond to those classified as cloud in the Landsat 'CFmask' layer (Zhu and Woodcock, 2012). To separate water from non-water pixels, we followed Ji et al. (2009) who recommend testing several indices and thresholds to identify the index and class boundaries that are most effective for the images and the area of interest. We computed surface water maps using a "0" threshold, and 0.1 increments either side of this up to +/−0.5 (i.e., −0.5, −0.4, −0.3, …, 0.5), for each index.

2.3.4. Landsat-Derived Reservoir Area and Volume Estimates

To derive reservoir area estimates from surface water maps, we used the connectedPixelCount function in GEE (Google Earth Engine, 2017) to extract a count of connected pixels classified as water by the GSW, NDWI, MNDWI1, and MNDWI2 over each of the 1200 identified reservoirs. The connectedPixelCount algorithm identifies adjacent pixels of the same value that share an edge, termed "4-way" connected, or adjacent pixels which share an edge or a corner, termed "8-way" connected. We used 4-

way rather than 8-way connections to reduce the possibility of stretches of river being included in the connectedPixelCount. The trade-off in this approach is under-estimates in area for reservoirs that have an irregular edge.

Reservoir water volumes can be estimated from reservoir extents by determining the empirical relationship between these two variables for a given reservoir (Li et al., 2016). In this study, volume equivalents were computed using the empirical method for relating reservoir surface area to volume derived by (Liebe et al., 2005), as per equation (4). Liebe and colleagues (Liebe et al., 2005) carried out bathymetric surveys at 41 small reservoirs in Upper-East Ghana, part of the Volta basin, and found that the following expression could explain 97.5% of observed variance between Landsat-derived surface areas of between 1 and 35 ha and measured reservoir volumes:

$$Volume = 0.00857 \times Area^{1.4367} \tag{4}$$

The Upper East region of Ghana where Liebe's study focused has a mean of 1.1% slopes, similar to the basin-wide mean of 0.9% slopes (USGS 15s elevation data).

2.3.5. Validation Data

To validate the Landsat-derived reservoir area estimates we used a dataset of reservoir extents that were digitised manually from Google Earth imagery. Google Earth provides high resolution (<15 m) images from multiple sources with most images in the collection are sourced from Digitial Globe's satellites (~2 m resolution). We derived the validation dataset by, first, randomly selecting 250 reservoirs from the 1200 identified in this study. Second, we digitised 347 reservoir extents corresponding to every date that imagery were available in the Google Earth historical imagery collection over the 250 reservoirs within the period May 2013 to October 2015. Google Earth images covering the entire reservoir extent were available for more than one month during this period at some reservoirs, and were not available for any month at other reservoirs. Of the 347 digitised

reservoir surface extents, 75 were excluded from subsequent analyses because: (i) they exceeded the neighbourhood search area in GEE's connectedPixelCount function, which is limited to 1024 pixels (92 ha); or, (ii) they were smaller than 0.09 ha, equivalent to one Landsat pixel, or; (iii) there were masked pixels in the underlying Landsat imagery, and therefore no Landsat-derived extent estimates against which to compare the validation data. Of the 250 randomly selected reservoirs, no suitable imagery were available over 48 reservoirs, while all of the digitized surface extents associated with a further 31 reservoirs were part of the 75 extents excluded from the validation dataset for one of the aforementioned reasons. The final validation dataset therefore contained 272 reservoir extents, from imagery acquired in different months across three hydrological seasons over 171 reservoirs. These validation extents ranged from 0.09 ha to 72.4 ha with a mean of 7.1 ha and median of 2.3 ha (lower QR: 0.8, upper QR: 7.1 ha), dispersed spatially and seasonally across the basin (Appendix A). As expected, the validation data were skewed towards dry months (October through March for most of the basin) when cloud-free images are more likely to be available in the Google Earth historical imagery collection. Reservoirs are smaller in dry months as water levels recede, which partly explain the high proportion of small reservoirs in the validation dataset. Because drying patterns can also depend on reservoir depth and catchment size, we calculated the catchment area for each reservoir and confirmed that the distribution of our validation dataset was representative of the distribution of basin-wide reservoir catchment sizes using the WaterWorld (Mulligan, 2013) zones of interest tool.

2.3.6. Accuracy Assessment

To assess the accuracy of reservoir area estimates derived from each surface water map (GSW, NDWI, MNDWI1, and MNDWI2), we compared the Landsat-derived reservoir areal extents and equivalent volumes to those in the validation dataset for corresponding image dates. We used the difference to compute the mean absolute error

(MAE), root mean square error (RMSE), and mean absolute percentage error (MAPE) of Landsat-derived reservoir area and volume estimates. We identified the optimal threshold for classifying reservoir water using NDWI, MNDWI1, or MNDWI2 as that which provides reservoir area estimates with the lowest mean area percentage error.

2.3.7. Analysis of Environmental Covariates

Accurate mapping of reservoir extents from Landsat imagery can be hindered by the methodological approach as well as environmental factors. Research on environmental sources of error in water classifications from Landsat data shows that green-brown water, arising for example because of suspended sediment or high chlorophyll content, reduces classification accuracy (Fisher et al., 2016). Our validation data were based on images from multiple sources available in Google Earth (e.g., WorldView, IKONOS, GeoEye, SPOT), making it challenging to visibly determine water colours of reservoirs in our validation dataset in a consistent manner. However, the Normalised Difference Vegetation Index (NDVI) (Rouse et al., 1973) is sensitive to fractional green vegetation cover (Carlson and Ripley, 1997) and may be a suitable indicator of surface or sub-surface vegetation. The geometry of the reservoir has also been identified as an important factor, with errors in water classification being higher on small or narrow reservoirs, or those with long perimeters (Fisher et al., 2016), since this increases the number of mixed water and non-water pixels, which are more susceptible to misclassification. We hypothesize that seasonal rainfall patterns may also introduce errors in reservoir extent analysis on a monthly timestep, since rainfall events can significantly alter reservoir extents overnight, increasing discrepancies between area estimates derived from Landsat and validation data, while cloud-cover during wetter periods of the year can obscure water pixels and lead to underestimates in reservoir area.

We ran a random forest regression tree analysis in R for each of the four methods that were used to generate reservoir area estimates from Landsat data, corresponding to

GSW and the optimal threshold identified (see Section 3.1) from applying NDWI, MNDWI1, and MNDWI2. We used percentage errors in reservoir area estimates as the dependent variable, and indicators of reservoir surface vegetation, reservoir geometry, and rainfall patterns as independent variables. In particular, as an indicator of reservoir surface vegetation, we used the mean NDVI from all pixels intersecting the reservoir extent, calculated in GEE from Landsat 8 OLI surface reflectance images acquired in the month each reservoir area estimate is made. We used reservoir area in hectares and reservoir perimeter-area ratio as recorded in our validation dataset, as indicators of reservoir size and shape. We used month and latitude as indicators of rainfall patterns. We selected the Random Forest approach (Breiman, 2001) as a statistical method for checking the relationship between a dependent and multiple independent variables, which accepts categorical and continuous data as well as correlated variables (such as reservoir size and perimeter-area ratio) as inputs. Random forest regression works by splitting the dataset into 63% test (bagged) data and 37% validation (out of bag) data, and then constructing multiple trees from random samples of the bagged data, such that the tree nodes represent decreasingly good predictors of the response variable (Cutler et al., 2007). Residual errors for each estimate are computed by comparing the predicted response against actual response for out of bag data. The trees are combined into a single tree whose nodes are ordered according to the importance of each variable in predicting the response. The "Importance" is a measure of prediction error that is divided by the standard error.

Results from the Random Forest were used to compare which variables were associated with errors in areal estimates, irrespective of the water classification method. In addition we assessed variation in MAPE for validation data stratified by 0.1 percentiles (ratio data) or classes (categorical data) for each factor.

2.3.8. Data Applications in Agricultural Landscapes

We used our GEE approach to extract area estimates for the 1200 identified Volta

basin reservoirs over the period 1984 to 2015 from GSW data, to test what information on reservoir volumes and seasonality could be determined given the limitations of data coverage and estimation errors.

We identified non-valid estimates, corresponding to months where pixels were masked or where no information was available in the underlying GSW data, and used these to assess the inter-annual, intra-annual and spatial availability of monthly reservoir area estimates. This information is used to evaluate whether there is sufficient data to obtain information on annual and intra-annual fluctuations in reservoir volumes and thus seasonality, which is useful for agricultural planning.

Next, we estimated the current maximum capacity for 1117 of the 1200 Volta basin reservoirs by identifying the largest extent recorded at these reservoirs between 1984 and 2015. We used one of the GSW derivative layers, the GSW Maximum Extent (GSW-MX), to get the maximum extent for the remaining 83 reservoirs whose maxima derived from GSW were ≥(92 ha—RMSE of area estimates), and therefore cannot be measured using our GEE approach, which is restricted to extents of less than 1024 pixels (~92 ha). The GSW-MX dataset highlights all of the pixels that have contained water at any time between 1984 and 2015. It was not available through GEE at the time of this analysis and so we extracted estimates from the GSW-MX in a desktop GIS. We assumed that reservoirs where no water was ever recorded are smaller than the minimum areal unit that can be reliably mapped using GSW data. Based on their maximums, we classified reservoirs as “Small” (<1 Mm^3), “Large” (⩾1 Mm^3 and <100 Mm^3), “Very large” (⩾100 Mm^3) or “Unknown” (no water identified in any month).

Finally, we analysed monthly fluctuations in area estimates for reservoirs where GSW-derived reservoir extents were available throughout the dry season in 2014–2015, the most recent hydrological year of data available, to distinguish the reservoirs that are perennial, ephemeral with 6–11 months water, and ephemeral with <6 months water within

estimate uncertainties. June, July, and August are rainfall months across the entire basin, and likely due to cloud cover, reservoir extent data were often missing over these months. Reservoirs with no valid observations for June, July and August were assumed to contain water during these months. Reservoirs with data missing for any month outside this period were excluded from the analysis, as were reservoirs with no water ever recorded during the 32 years covered by the dataset. The monthly rate of water loss can be obtained from GSW-derived reservoir area estimates by subtracting the annual minima from the maxima, and dividing this by the number of months between the two extremes. Where the monthly water loss was less than the uncertainty contained in the reservoir area estimates, as estimated by the RMSE, we assumed the estimates cannot be reliably used to monitor the loss in reservoir water through the year and classified its seasonality as "uncertain".

GEE codes that were used in our analyses are available here: https://earthengine.googlesource.com/SurfaceWaterMapping. R codes used to calculate estimation errors and the random forest analyses are available on request.

2.4. Results

2.4.1. Accuracy of Reservoir Area Estimates

Comparing reservoir area estimates from GSW, NDWI, MDNWI1, and MNDWI2 against those in our validation dataset, we find that estimates varied substantially in accuracy across methods. Careful selection of the threshold for water classification is critical for minimizing percentage errors in reservoir area estimates derived from NDWI, MNDWI1, and MNDWI2. The lowest MAPE was achieved using a threshold of −0.2 on both the NDWI and MNDWI1, and a 0 threshold on MNDWI2 (see Appendix C for comparative accuracies of NDWI, MNDWI1, and MNDWI2 across all thresholds). We subsequently refer to results from NDWI, MNDWI1 and MNDWI2 corresponding to these optimal thresholds.

Comparison of absolute errors in reservoir area estimates indicates MNDWI1

produced slightly better estimates than the other three approaches. Estimates using MNDW1 had an RMSE of 3.0 ha equivalent to 22,581 m^3, and an MAE of 1.7 ha (10,085 m^3), while estimates from the GSW had a nearly two-fold higher RMSE of 5.1 ha (49,376 m^3) and an MAE of 2.8 ha (20,786 m^3). Small absolute errors can mask large percentage errors in area estimates. Moreover, a high percentage area error can translate to an even higher percentage volume error, since reservoir area and volume are related through a power relationship. Comparing percentage errors indicates that MNDWI1 still out-performed other approaches, producing estimates with a mean absolute percentage error at 51%, which equates to a mean volume percentage error of 58%. The GSW method had a higher MAPE than all three water indices tested, producing estimates with a mean area percentage error of 70%, which equate to a 75% mean volume percentage error. In other words, reservoir area estimates that were derived from the GSW dataset using our method were 19% less accurate that those that can be derived by applying MNDWI1 to Landsat 8 OLI imagery, resulting in 17% less accurate reservoir volume estimates (see Table 4).

Table 4. Accuracy of 272 reservoir areal extents and volume equivalents derived from Global Surface Water Monthly Water History (GSW), Normalised Difference Water Index (NDWI), Modified NDWI with band 6 (MNDWI1), and Modified NDWI with band 7 (MNDWI2).

Method	**Threshold**	**Mean Error (ha)**	**SD (ha)**	**RMSE (ha)**	**RMSE (m^3)**	**MAE (ha)**	**MAE (m^3)**	**MAPE (% Area)**	**MAPE (% Volume)**
GSW	–	−2.7	4.3	5.1	49,376	2.8	20,786	70.3	75.1
NDWI	−0.2	−2.1	3.5	4.0	35,605	2.4	16,325	64.4	69.6
MNDWI1	−0.2	−1.3	2.6	3.0	22,581	1.7	10,085	51.2	58.3
MNDWI2	0	−1.3	2.8	3.0	24,041	1.8	10,705	52.7	60.1

The additional overall inaccuracy of the GSW method when compared to MNDWI1 was associated with a higher number of omission errors, i.e., 100% under-estimates (Table 5). In total 140 (51%) reservoir areas were omitted using the GSW-derived estimates, as compared to 82 using those from MNDWI1. These 100% GSW-derived underestimates occurred over very small reservoirs: 75% were smaller than 2.9 ha (~21,788 m^3), and the median reservoir area was 1.0 ha. In contrast, 100% underestimates in MNDWI1-derived

reservoir areas occurred on reservoirs with a median area of 0.7 ha and 75% of which were smaller than 1.5 ha (~8396 m^3).

Table 5. Number and type of errors in reservoir area estimates (n=272) derived from GSW, NDWI, MNDWI1, and MNDWI2.

Method	Omissions (100% under-Estimate)	Under-Estimates (by <100%)	Over-Estimates
GSW	140	121	11
NDWI	124	123	25
MNDWI1	82	153	37
MNDWI2	86	148	38

2.4.2. Environmental Covariates

We analysed how the accuracy of reservoir area estimates from GSW, MNDWI1, MNDWI2, and NDWI vary with environmental conditions. Factors included in the random forest regression analysis explained 63% of variance in reservoir area percentage estimation errors for GSW when compared to 49% for MNDWI1, 41% for MNDWI2 and 72% for NDWI. Mean NDVI over the reservoir was identified as the most important variable in all of the cases, followed by reservoir extent and perimeter-area ratio (i.e., reservoir geometry). Latitude was the next most important factor, while month of year was of least importance to improving accuracy under all of the methods (Figure 7).

Reviewing the MAPE for reservoir area estimates from GSW, NDWI, MNDWI1, and MNDWI2 as environmental factors vary gives an indication of when area estimates are most accurate and when estimates from GSW are comparable in accuracy to other methods. We stratified reservoir area estimates into 0.1 percentile classes for each factor that was included in the random forest analysis and compared variance in mean absolute percentage errors across each class (see Figure 8).

Results show that area estimates from MNDWI1 and MNDWI2 were more accurate than those from GSW, while accuracies of GSW and NDWI are similar, under all of the conditions. For all of the methods, percentage errors increased with NDVI and with reservoir perimeter-area ratio, and reduced with increasing reservoir size. Percentage

errors were lower at mid-latitudes across all of the methods, and relatively stable through the year except in July and September where there was high variability across methods. Errors in GSW estimates were lower than average when mean NDVI ≤ 0.09; reservoir area is >3.64 ha, reservoir perimeter-area ratio is ≤0.32.

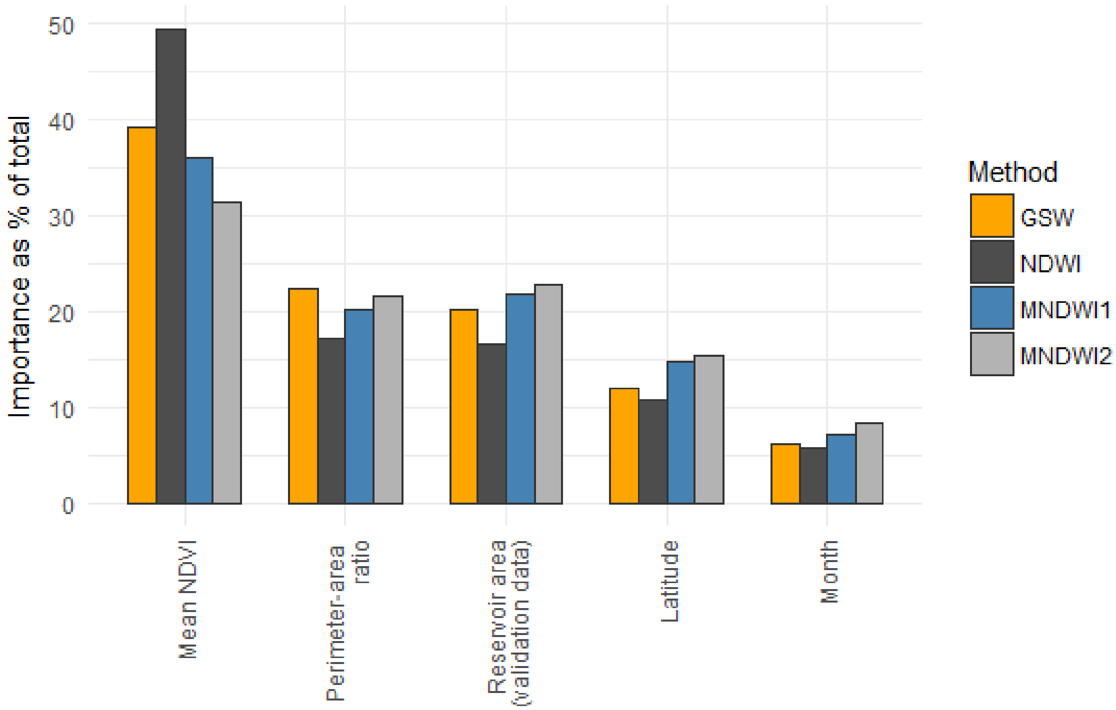
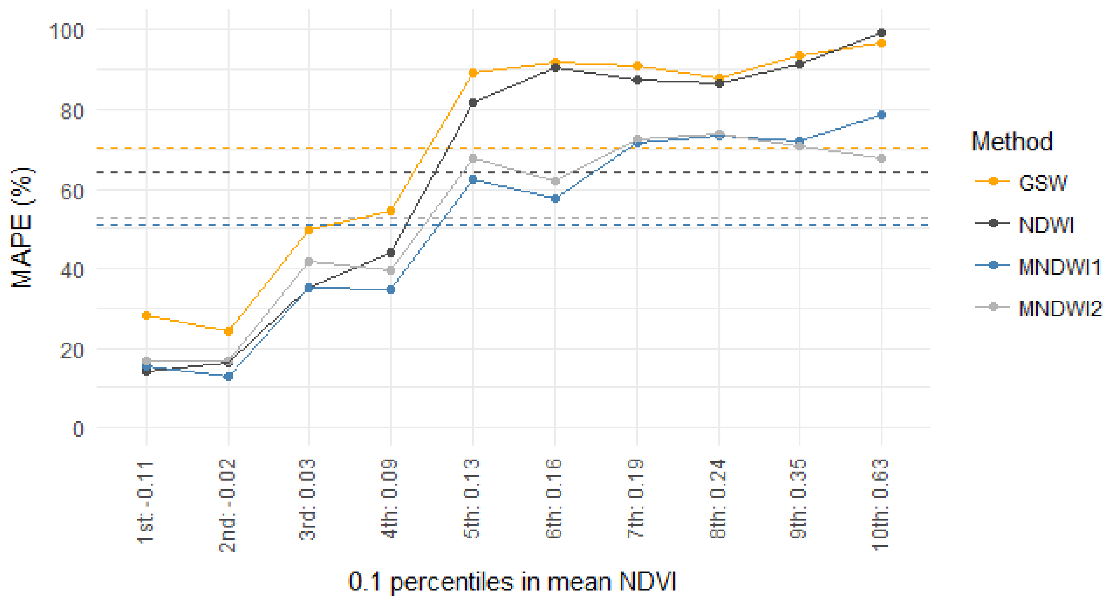
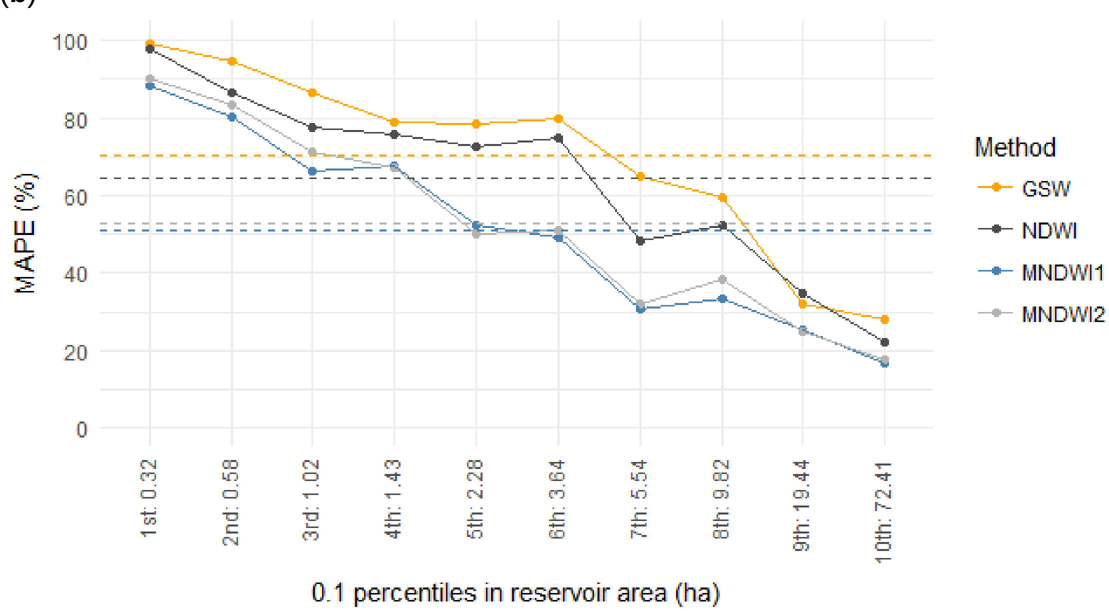


Figure 7: Importance (as percentage of total across all variables) of five environmental variables in producing accurate reservoir area estimates, as calculated by a random forest regression analysis of percentage errors in reservoir area estimates from GSW, MNDWI1, MNDWI2, and NDWI on mean NDVI, perimeter-area ratio, reservoir area, latitude and month.

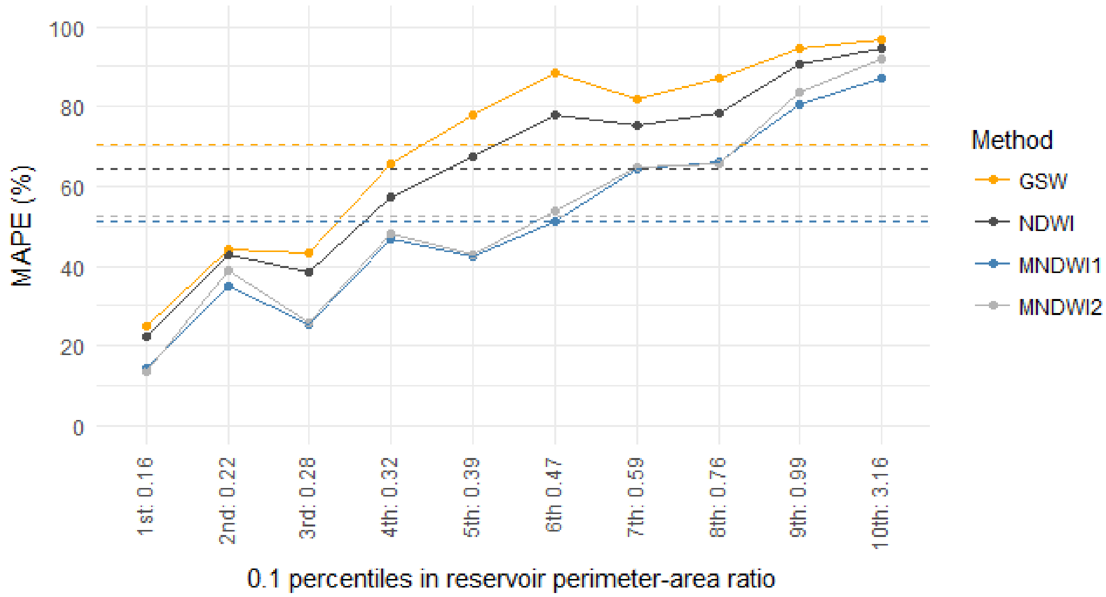
(**a**)


100
80
60
40
20
0
MAPE (%)
1st: -0.11
2nd: -0.02
3rd: 0.03
4th: 0.09
5th: 0.13
6th: 0.16
7th: 0.19
8th: 0.24
9th: 0.35
10th: 0.63
0.1 percentiles in mean NDVI
Method
GSW
NDWI
MNDWI1
MNDWI2

(**b**)

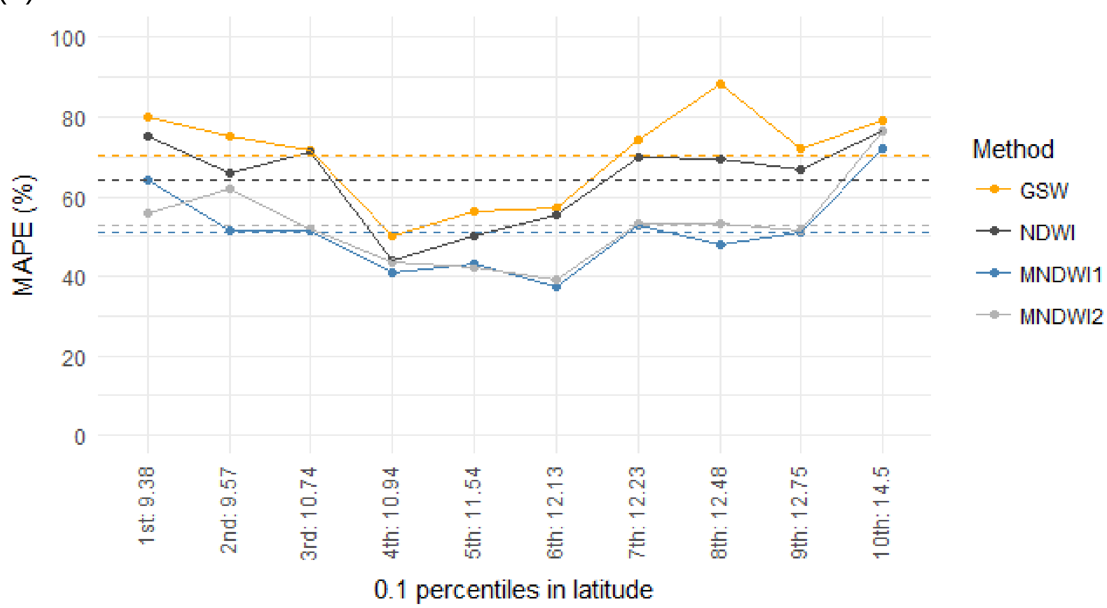

100
80
60
40
20
0
MAPE (%)
1st: 0.32
2nd: 0.58
3rd: 1.02
4th: 1.43
5th: 2.28
6th: 3.64
7th: 5.54
8th: 9.82
9th: 19.44
10th: 72.41
0.1 percentiles in reservoir area (ha)
Method
GSW
NDWI
MNDWI1
MNDWI2

(**c**)



MAPE (%)
100
80
60
40
20
0
1st: 0.16
2nd: 0.22
3rd: 0.28
4th: 0.32
5th: 0.39
6th 0.47
7th: 0.59
8th: 0.76
9th: 0.99
10th: 3.16
0.1 percentiles in reservoir perimeter-area ratio
Method
GSW
NDWI
MNDWI1
MNDWI2

(**d**)



MAPE (%)
100
80
60
40
20
0
1st: 9.38
2nd: 9.57
3rd: 10.74
4th: 10.94
5th: 11.54
6th: 12.13
7th: 12.23
8th: 12.48
9th: 12.75
10th: 14.5
0.1 percentiles in latitude
Method
GSW
NDWI
MNDWI1
MNDWI2

(e)

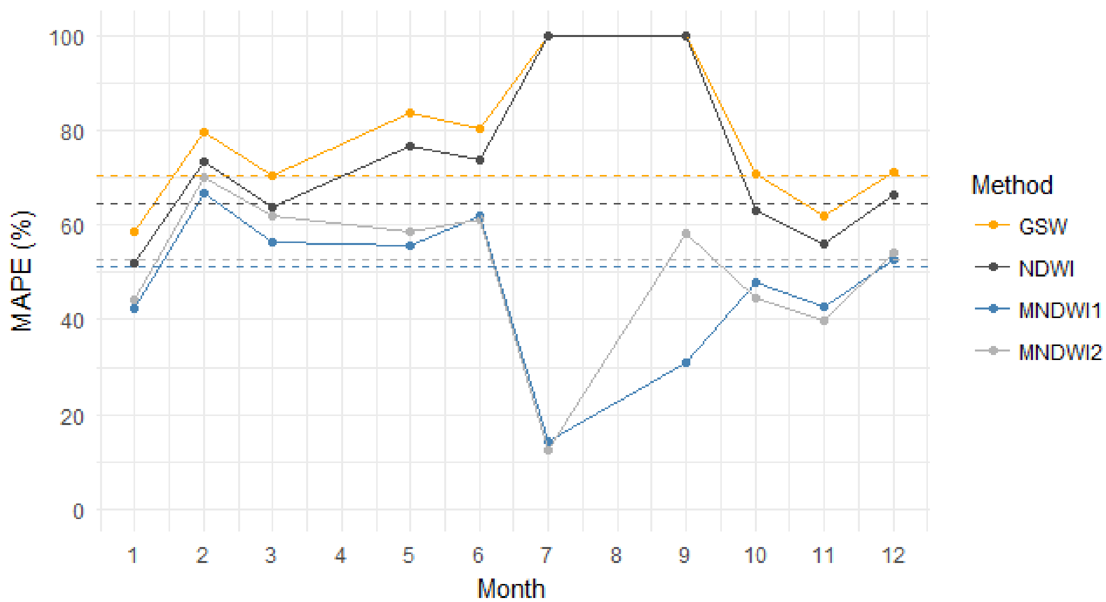


Figure 8: Mean absolute percentage error (MAPE) in reservoir area estimates derived from the four water classification methods (GSW, NDWI, MNDWI1, MNDWI2) when validation reservoirs are stratified by (a) mean NDVI, (b) reservoir area, (c) perimeter-area ratio, (d) latitude, and (e) month. Dashed lines indicate the overall MAPE corresponding to each method.

2.4.3. Applications of Reservoir Extent Data in Agricultural Landscapes

In total, 380 months of data are embedded in the March 1984 to October 2015 GSW dataset. However, there were substantial gaps in coverage over specific reservoirs and time periods in our derivative reservoir extent layer. Individual reservoirs had between 47% and 87% missing data across the 380 months; or, 74-98% pre-2000 and 18-77% from 2000 onwards. Gaps were concentrated in the period 1984–1999, indicative of gaps in the underlying USGS Landsat image archive (Goward et al., 2001) specifically over West and north Africa (Wulder et al., 2016). Data availability increased with latitude, likely being a result of decreasing cloud cover. Data gaps of over 50% were present in most years during peak rainfall months, from June to September, when cloud-cover may prevent accurate water classification. The bias towards reservoir area estimates in dry season months means annual mean and maximum reservoir areas will be underestimated, especially for reservoirs that dry up quickly after rains cease (e.g., very small reservoirs). Individual reservoirs had one or more valid area estimate per year (i.e., one month or more of data)

for between 19 and 28 of the 32 years, meaning there were whole years of no data at every reservoir. While at most reservoirs the years of missing data are pre-2000, data coverage was very low in some subsequent years, including 2003 and 2012. Even in years with valid observations if these are from the dry season then they can be 0 ha, indicating an absence of water. Further details on data coverage are provided in Appendix B.

Reservoir capacities as indicated by the maximum extents ever recorded show that at 339 reservoirs, the reservoir areas were permanently recorded as 0 ha, and were therefore assumed to be reservoirs smaller than the minimum mapping unit for GSW. Including these 339 reservoirs, 674 (56%) of the basin's reservoirs were smaller than 5.1 ha, the RMSE for GSW-derived estimates, while an estimated 1055 (88%) of the basin's reservoirs are smaller than 41.2 ha (1 Mm^3) (see Table 6). At their maximums, small reservoirs cover 6618 ha of the Volta basin, collectively holding 1476 Mm^3 of water. This equates to about 0.1% of the total water stored in reservoirs in the Volta basin, or 16% if the 13 very large reservoirs (>100 Mm^3) are excluded. The mean area that is covered by these small reservoirs at their maximum extents is 9.2 ha (SD = 10.0 ha), with each estimated to contain 116,780 m^3 water, equivalent to 47 Olympic swimming pools.

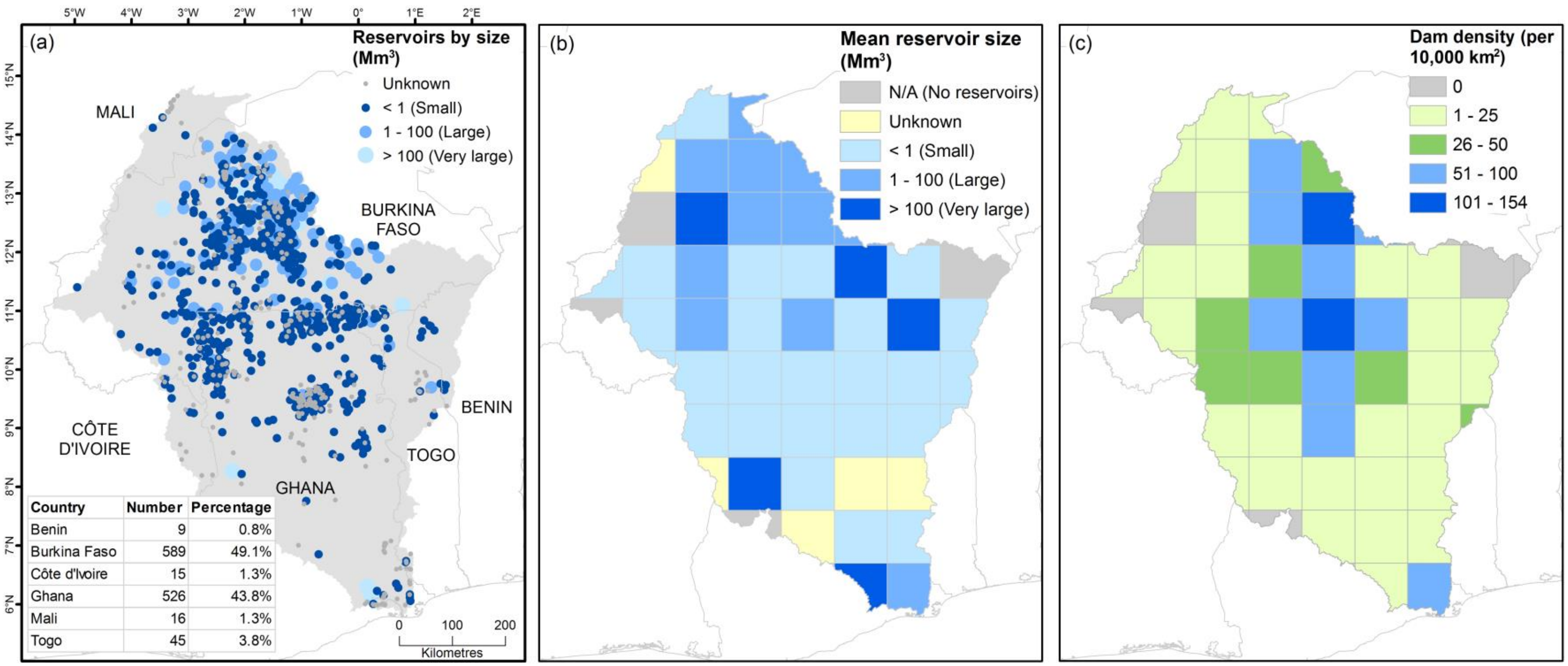
Table 6. Reservoir number and size based on their maximum GSW-derived extents, providing an indication of reservoir capacity and an upper limit for current reservoir size. Volumes are calculated using Equation (4).

Type	Size	Number	Mean Area (ha)	Mean Volume (m^3)	Total Area (ha)	Total Volume (m^3)
Small	Unknown (likely very small)	339	-	-	-	-
	<41.2 ha (1 Mm^3)	716	9.2 (SD = 10.0)	116,780 (SD = 130,197)	6618	1475.8 M
Large	41.2 (1 Mm^3)–1016.3 ha (100 Mm^3)	132	157.0 (SD = 163.1)	6.8 M (7.2 M)	20,728	7610.0 M
	>1016.3 ha (100 Mm^3)	13	63,511.7 (SD = 197,167.2)	38,022.5 M (SD = 193,584.2 M)	825,652	1,515,106.4 M
All	-	1200	-	-	852,998	1,524,192.0 M

Over 92% of the identified reservoirs are located in Burkina Faso or Ghana.

Reservoir density is higher (>50 per sq km) in the southern tip and central corridor of the basin, while reservoirs are, on average, substantially larger towards the north of the basin, in Burkina Faso, and in pockets of southern and western Ghana. Small reservoirs dominate the central plains (see Figure 9). While the volumes that are contained in small reservoirs are relatively small, their spatial dispersion means they make water accessible to people in many otherwise unserviced parts of the basin, which includes some of the basin's poorest households and driest landscapes.

The presence of a reservoir does not assure that it contains water throughout the dry season, information that is important for water scarcity mapping and agricultural planning. The large intra-annual data gaps and uncertainties in GSW derived reservoir extent data make it challenging to monitor the rates of change in reservoir area and equivalent volumes, for example to identify the month a reservoir runs dry. However, this is possible at reservoirs where data exist throughout the dry season in a single hydrological year. We find that, excluding June, July, and August, which correspond to rainfall months throughout the basin, and excluding reservoirs where no water was ever recorded between 1984 and 2015, GSW derived reservoir areas are available for every month for 350 reservoirs in the 2014–2015 hydrological year. Area estimates from September 2014 to May 2015 show that 256 of these reservoirs had a monthly area loss equal to or smaller than the 5.1 ha RMSE for GSW-derived estimates, and therefore their seasonality cannot be reliably determined. Of these 256 reservoirs, 255 were classified as Small and one as Large based on their maximum volumes (see Table 6). For the remaining 94 reservoirs, of which 30 were Small and the others Large or Very Large, and 25 were perennial while 69 were ephemeral running dry for up to seven months of the year (see Figure 10).



Country	Number	Percentage
Benin	9	0.8%
Burkina Faso	589	49.1%
Côte d'Ivoire	15	1.3%
Ghana	526	43.8%
Mali	16	1.3%
Togo	45	3.8%

Figure 9: (a) Reservoir locations and size, (b) mean reservoir size, and (c) reservoir density across the six Volta basin countries.

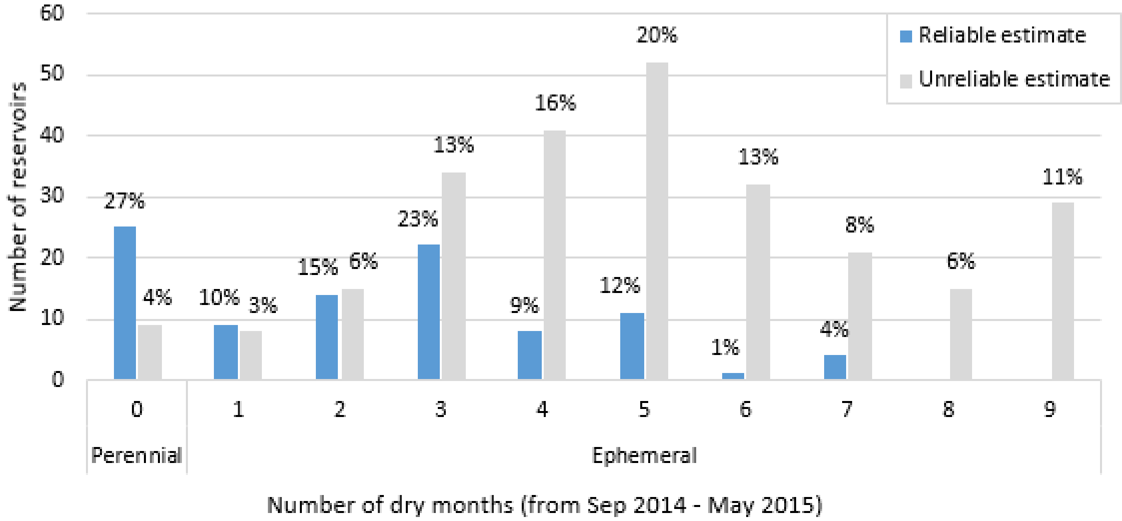


Figure 10: Seasonality of a subset of reservoirs (n = 350), for which valid GSW derived reservoir area estimates were available from September 2014 to May 2015. The figure shows the number of months a reservoir was recorded as dry distinguishing reservoirs where the mean monthly change in area was larger than the root mean square error (RMSE) in GSW derived area estimates ("Reliable estimate", n = 94) from reservoirs where the monthly area change was equal to or smaller than the RMSE ("Unreliable estimate", n = 256).

2.5. Discussion

2.5.1. Accuracy of Reservoir Extents Derived from Landsat-Based Surface Water Maps

Landsat-derived reservoir area estimates contain uncertainty with even MNDWI1, the best performing of the water classification methods that were tested, producing estimates with a MAPE of 51%, for reservoirs between 0.09 ha and 72 ha in extent. Reservoir area estimates from MNDWI1, which uses Landsat 8 OLI band 6, are 1.6% more accurate than those from MNDWI2, which uses Landsat 8 OLI band 7, and 13% more accurate than those derived from the NDWI. In contrast, GSW produces area estimates with a MAPE of 70%, or 19% less accurate than those derived from MNDWI1.

These results indicate that exploiting the difference between visible and short-wave infrared light, rather than visible and infrared, is preferable for surface water mapping in the Volta basin. This may be because the difference in the amount of infrared light reflected from pure water and from vegetation is small relative to the difference in short-wave infrared light reflected (Xu, 2006), and crops and other waterline vegetation are prevalent around dryland reservoirs. The results further indicate that bands with shorter wavelengths slightly out-perform those with longer as short-wave infrared inputs to the MNDWI for mapping surface water extents from Landsat satellite imagery, as consistent with (Du et al., 2014; Ji et al., 2009). The higher uncertainty in GSW-derived area estimates indicates that the water classification algorithm used in creating the GSW datasets is less effective at distinguishing water from non-water pixels than NDWI or MNDWI using Landsat 8 OLI imagery, for our West African study site. Further research is required to check whether this result holds for other sensors and dryland regions.

For NDWI, MNDWI1, and MNDWI2, we find that careful selection of the threshold for water classification is critical to reduce errors in reservoir area estimates. Across all three spectral indices, the accuracy of reservoir area estimates varies significantly with

thresholds between −0.5 and 0.5. The commonly used zero-threshold for water classification is sub-optimal for two of the three water indices that were tested, NDWI and MNDWI1, for which use of a slightly negative (−0.2) threshold produces superior reservoir area estimates. This may be because while pure water normally reflects little or no infrared or short-wave infrared light, the inverse is true for both vegetation and soil (Baldridge et al., 2009). Therefore, water with suspended sediment or high chlorophyll concentrations, likely to be common in dryland reservoirs in agricultural landscapes that are exposed to both accelerated erosion and nutrient runoff (Lal, 2001), may reflect more infrared and short-wave infrared light than clear water. This increases the possibility of a slightly negative difference between visible and infrared or short-wave infrared light.

Reservoir area estimates from MNDWI1 and MNDWI2 are more accurate than those from GSW under all of the conditions tested in this study, while estimates from NDWI slightly outperform those from GSW, except in a few cases, such as for larger reservoirs (see Figure 8). Percentage errors in reservoir area estimates increase with NDVI and with reservoir perimeter-area ratio, and reduce with an increasing reservoir size, for all four water classification methods. Since NDVI responds to green vegetation cover (Carlson and Ripley, 1997), it is likely that surface or sub-surface vegetation is responsible for an increase in errors with mean NDVI. We expect the poor performance of all the methods on very small reservoirs and those with a high perimeter to area ratio is due to the 30 m resolution of Landsat data, limitations in pixel-based water-classification algorithms, and our automated approach that extracts connected water features above a pre-defined point. Reservoir area estimates have lower percentage errors at mid-latitudes of the Volta basin across all of the methods, which might be a result of higher annual cloud cover in the south and higher airborne sand and dust levels in the north hindering water classification. Percentage errors in reservoir area estimates from GSW and NDWI show a sudden increase in wetter months, while those from MNDWI1 and MNDWI2 show a sharp decline.

This result is partly a reflection of the superior performance of MNDWI1 and MNDWI2 over very small reservoirs, since all of the reservoirs from July to September are <7.6 ha with a median of 3.5 ha, however it may also be symptomatic of shortcomings in GSW and NDWI water classification approaches over the turbid waters that are associated with heavy rainfall.

2.5.2. Conditions Under Which GSW Can Provide Reliable Information on Reservoir Size and Seasonality

Results of the random forest and subsequent analysis of percentage error variance with environmental conditions show that controlling for surface water vegetation (as indicated by NDVI) and reservoir size and shape would improve the reliability of area estimates from GSW, since these are the main factors underpinning 63% of the variance in percentage errors. Users can apply thresholds for NDVI and reservoir size and shape to identify when reservoir area estimates have an unacceptable error depending on the end-use, or when errors are lower than average and therefore reliability increases. For example, in our study, percentage errors in GSW estimates were lower than average when mean NDVI ≤ 0.09, reservoir area >3.64 ha, and reservoir perimeter-area ratio ≤ 0.32.

Correctly identifying when a reservoir contains water during the year is necessary for seasonality analyses and for determining reservoir locations if these are unknown. Our analysis shows that GSW produces reservoir area estimates with a RMSE of 5.1 ha, meaning that if a reservoir extent changes by ≤5.1 ha, this change may not be detected in GSW-based analyses of reservoir size. For reservoirs ≤5.1 ha in extent, the equivalent loss in volume is ≤49,759 m^3, while for larger reservoirs, any loss in area would occur in the shallowest regions and therefore represent a smaller equivalent loss in volume. In contrast, reservoir areas estimated from MNDWI1 in this study had an RMSE of 3.0 ha, equivalent to 24,041 m^3. Further, if a reservoir extent is equal to or smaller than the RMSE for any given month, the reservoir may be incorrectly identified as dry introducing additional

uncertainty to seasonality analyses (see Figure 10). Indeed, we find that the presence of water in very small reservoirs, specifically those under 2.9 ha for GSW estimates and under 1.5 ha for MNDWI1 estimates, is often entirely missed using Landsat-based water classification approaches. The omission of many small waterbodies in national or global inventories will lead to inaccurate surface water accounting and may hinder government or NGO ability to target dam construction and maintenance effectively or allocate water resources in a socially and environmentally sustainable manner. Moreover small surface waterbodies can have surprisingly large-scale cumulative effects on hydrological and ecosystem processes (Downing, 2010), including altering downstream water supplies, trapping sediment, and impacting on global greenhouse gas emissions (Holgerson and Raymond, 2016; Messager et al., 2016).

Knowing the reservoir size constraints that are associated with a selected method is important for agricultural and water resource management planning, particularly in landscapes with small reservoirs. For example, our results indicate there are 674 reservoirs in the Volta basin with a GSW-estimated maximum capacity of 49,759 m^3 (5.1 ha), for which GSW-derived size estimates are not reliable and complete omissions of reservoir water presence are likely. Further, of 350 reservoirs where continuous monthly area estimates were derived from GSW through the 2014–2015 dry season, reliable estimates of intra-annual dry periods could be obtained for only 30 of the 285 reservoirs that were classified as small since all of the other small reservoirs had a monthly area loss of less than 5.1 ha. However, even when the quantity of water cannot be reliably measured, the presence or absence of water may still be correctly identified since the RMSE will be inflated by errors at larger reservoirs. As a minimum, end-users should indicate the expected uncertainty in area or volumes derived from GSW, for example, based on the RMSE or a similar measure. This can be used to indicate when the size of a reservoir or change in reservoir size drops below the size of the estimation error and thus estimates

are unreliable.

2.5.3. Value of a Mixed-Methods Approach

We developed a method for remotely mapping small reservoirs, monitoring reservoir extents through time, and quantifying uncertainty in these extent estimates, that uses freely available data and tools. The added value of this method over previous attempts to monitor surface water dynamics is that it can be easily repeated anywhere to improve global reservoir data and establish rates of uncertainty in Landsat-derived reservoir extent estimates for other contexts and regions of interest. Our results indicate studies that rely solely on Landsat or coarser resolution data to map surface water dynamics will omit smaller reservoirs. Integrating data from freely available high resolution imagery or ground-based monitoring systems is a practical, low-cost approach to ensuring reservoirs of all sizes are captured in Landsat-based water resource assessments. We show that reservoirs can be mapped manually through freely available Google Earth imagery - which could be completed using crowd-sourcing techniques (for example, see http://geodata.policysupport.org/geowiki-databases) - allowing for reservoir capture over large spatial extents.

As well as reducing gaps in reservoir inventories, mapping reservoirs prior to analysis of surface water maps enables application of simple waterbody extraction algorithms, such as the connectedPixelCount in GEE, significantly reducing the time required to extract data over large spatio-temporal extents. Using a server-based approach also avoids the significant computer storage and processing requirements that create challenges to analyses of multiple Landsat images (Gorelick et al., 2017; Ogilvie et al., 2016; Pekel et al., 2016). GEE is particularly useful for the analysis of many Landsat images, since each Landsat image is ~1 GB in size with a footprint of approximately 185 km^2 and collected on a 16-day time step, so temporal analyses over large areas require hundreds of gigabytes of imagery. Access to Landsat satellite imagery, GSW datasets, and

image processing algorithms through server-based tools such as GEE, once the software learning curve is surpassed, significantly reduces the time and cost that is involved in deriving and comparing the accuracy of waterbody extents across time and space.

Data gaps in the reservoir area estimates from the GSW Monthly Histories dataset over the Volta basin limit the types of information that can be gathered from this resource. Most of these gaps are caused by missing imagery in the underlying Landsat archive (Wulder et al., 2016), and therefore would not be avoided by applying an alternative water classification method on Landsat satellite imagery. Other gaps represent areas that are classified as non-valid by Pekel et al. (2016), e.g., cloud or shadow. Time series interpolation at distinct reservoirs, for example using Amelia (Honaker and King, 2010), can produce estimates of missing monthly reservoir areas, but levels of uncertainty are likely to be high over many reservoirs and years due to the large data gaps. The most promising solution to filling time-series data gaps - in the absence of access to additional Landsat and other historical satellite data (Wulder and Coops, 2014) - is probably by integrating water classifications from Landsat data with those produced from lower resolution optical imagery, such as from MODIS (Khandelwal et al., 2016), while seasonal gaps may be reduced by integration with water classified using synthetic aperture radar data, such as from Sentinel-1 (Pham-Duc et al., 2017), since these are not sensitive to periods of cloud cover.

2.5.4. Policy Applications in Agricultural Landscapes

In the Volta basin, applying our approach shows that the availability of small reservoir water is currently highly uneven across space and through the seasons. For example, dam density is higher in central Burkina Faso and northern Ghana, while some of the northern, western, and eastern regions of Burkina Faso, despite being among the driest in the Volta basin, are served by far fewer reservoirs. However, the extent of the gaps in GSW-derived data, which cover entire years for many reservoirs, limit its use for

monitoring long-term trends in reservoir water availability. For some policy applications, this may not present a constraint, since long-term trends will be of less interest than analyses that show current conditions and short-term fluctuations, which can be derived from data post-2012 when underlying coverage is much higher in the GSW dataset for our West African site, and imagery from Landsat 8 OLI are available. Even without data gaps, agricultural policy applications in landscapes with small reservoirs, such as the Volta basin, where our analysis indicates 88% of reservoirs are <1 Mm^3, remains a challenge since the level of uncertainty in GSW and other Landsat derived reservoir areas hinders reliable seasonality analyses and can result in omissions of whole reservoirs.

2.5.5. Limitations of Our Approach

While our approach to obtaining time series reservoir extents can be rapidly applied over large spatio-temporal extents through GEE, it relies on the prior identification of dam locations. For this study, we mapped dams from the most recent imagery available in Google Earth in 2015. Dams that were subsequently constructed, or previously constructed and are now out of use, are not captured in our analysis. Automating the identification of reservoir locations would be a faster approach, however we have demonstrated that water classification maps from Landsat imagery are unable to reliably detect reservoirs <2 ha, which constitute over a third of reservoirs in the Volta basin. A useful future step would be to explore the potential for using higher resolution imagery, particularly from the Sentinel-2 satellite (10 m resolution), to automate the identification of small reservoirs.

Gaps in the 32-year reservoir extent data derived from GSW-MH arise from masked pixels (e.g., cloud or haze-covered) or a lack of imagery in the underlying Landsat collection (Pekel et al., 2016). Additional gaps may arise from our automated area-extraction method where the reservoir point is outside the reservoir water extent. Missing data in monthly reservoir area estimates distorts individual and population reservoir storage

means, maximums, and minimums, and therefore limits the utility of the dataset for monitoring changes in reservoir surface areas through time.

In addition to missing values in the GSW-MH dataset, a limitation of our method is that the connectedPixelCount algorithm in GEE used to extract reservoir extents can handle up to 1024 connected pixels, meaning that reservoirs that cover a larger area will be underestimated. For Landsat data at 30 m resolution, this area limit is equivalent to 92.16 ha. This is substantially larger than the 41.2 ha upper size limit for small reservoirs, but creates a problem for the analysis of larger waterbodies. Reservoir estimates for these reservoirs can either be obtained by reducing the resolution (and therefore the number of pixels covered by a reservoir) on underlying Landsat imagery over larger reservoirs to enable use of the connectedPixelCount algorithm, or performing the analysis in a desktop GIS.

2.6. Conclusion

Reservoirs can provide a lifeline to the basin's rural poor during dry spells and seasons, generating stable sources of food and income through livestock, fish, and crop production. But households that depend on small reservoirs for their livelihoods do so at substantial risk. In years with low rainfall or heavy withdrawals, there may not be enough water to complete the dry season cropping season, to water livestock, or to sustain fish populations. Crop failure or fish decline means the loss of food and income at the household and community level. Lack of livestock water forces seasonal migration often to areas with their own land and water resource management challenges. Monitoring the distribution and seasonality of reservoir water on a regular basis through remote methods in the Volta basin and elsewhere is a cost-effective way for governments and non-governmental organisations to identify high risk zones. This knowledge may facilitate the implementation of safeguards to minimise water shortages and food losses, and can be used to inform decisions on future dam investments.

We developed a semi-automated method for mapping reservoirs and their extents through time, and assessing uncertainty in Landsat-derived reservoir size estimates, which can be readily applied anywhere in the globe using freely available data and tools. We used our method to compare estimates of reservoir area that were derived from four approaches to classifying surface water from Landsat data. These include the approach that was used to create the Global Surface Water Monthly Water History (GSW) datasets (Pekel et al., 2016), and surface water maps created in this study from Landsat 8 OLI imagery by computing the Normalised Difference Water Index (NDWI) and two variations of the Modified NDWI, which employ band 6 (MNDWI1) and band 7 (MNDWI2) as the short-wave infrared inputs, testing effects of classifying water across 11 thresholds. We find the mean absolute percentage error is 71% for reservoir area estimates derived from GSW data, tested over 272 reservoirs between 0.09 ha and 72 ha in extent. The accuracy of these reservoir areal estimates can be improved by up to 19% by classifying water pixels on Landsat 8 OLI imagery using MNDWI1 with a carefully selected threshold, and improved to a lesser degree using NDWI or MNDWI2. Estimates that are derived from MNDWI1 consistently out-perform estimates from GSW as reservoir geometry, vegetation characteristics, and measurement season vary. Our results imply that the expert system classifier used to identify water pixels in creation of the GSW is sub-optimal to using any of the three water indices tested here, for images from the Landsat 8 OLI and over our West African study site. Further research is required to check whether this result holds in other contexts, and for imagery that is collected by the Thematic Mappers and Enhanced Thematic Mapper onboard Landsat satellites 4, 5, and 7.

Our study provides new information on the reliability of reservoir size and seasonality from GSW and other Landsat-based surface water maps, which is important given that these data are freely and globally available and use of information on reservoir resources for policy making without the knowledge of inherent uncertainties may have

serious consequences. Whether or not it is important to have the 19% increase in accuracy in reservoir area estimates obtained from using surface water maps generated by applying MNDWI1 to Landsat 8 OLI images, rather than using the pre-prepared GSW data, depends on the end-use. For agricultural planning and seasonal water resource management, we recommend that the use of GSW estimates be restricted to reservoirs with a maximum volume and monthly water loss of >49,759 m^3 (5.1 ha), to avoid masked or false detection of water shortages. Further, Landsat-based approaches are often unable to detect any water in very small reservoirs, namely those <1.5 ha using MNDWI1 and <2.9 ha using GSW. New opportunities for the remote monitoring of small reservoirs are opening up with the availability of Sentinel-1 radar and high resolution (up to 10 m) Sentinel-2 optical data, which together should help to reduce spatial and seasonal data gaps, and improve the accuracy of derived reservoir area estimates. In the meantime, adopting integrated approaches to mapping small reservoirs remotely, such as manual digitising reservoir locations from high resolution imagery combined with automated reservoir extent extraction from Landsat imagery, is essential to avoid entirely omitting numerous water bodies.

3. Dry season irrigated cropping at small and medium sized reservoirs

Improving access to agricultural water is a primary motivation for investments in reservoirs in semi-arid areas. Chapter 2 showed that there are 1200 reservoirs distributed across the Volta basin opening up opportunities for irrigated cropping. To understand where reservoirs are effectively leading to increases in smallholder crop production, this chapter develops and tests methods to determine the dry season irrigation status (presence, location, extent) of community managed reservoirs in the basin.

3.1. Abstract

Several micro studies in the Volta basin have shown irrigation uptake and productivity at small, community-managed reservoirs is lower than expected. It is unclear whether these trends are typical of reservoirs across the basin since no basin-wide datasets exist documenting reservoir irrigation activities. Investments in manmade reservoirs are costly and associated with negative environmental (e.g. reduced river flows, disrupted aquatic ecosystems) and social (e.g. population displacement, waterborne disease risks) impacts. Methods to monitor their impact on irrigation uptake would help determine the effectiveness of community-managed reservoir investments for boosting crop production and verify the benefits of these investments outweigh the costs. This study develops and tests three Google Earth Engine-based approaches to using time-series Normalised Difference Vegetation Index (NDVI) for delineating dry season irrigated cropland proximate to Volta basin reservoirs, using imagery from the Landsat 8 and Sentinel 2 satellites. Results show that, while high overall classification accuracies where achieved (88-96%), commission errors lead to a very high number of incorrect detections of irrigation presence and over-estimates in irrigated area. Manual approaches to irrigated cropland detection and delineation using Google Earth Pro imagery were found to be a robust alternative and represent the most reliable solution to reservoir irrigation impact

assessment until methodological challenges in automated detection are overcome. Using the manual approach, irrigation was detected at 46% of small and medium reservoirs (n = 1155) across the Volta basin and total irrigated area amounts to 5588 ha. This low irrigation uptake rate highlights a pressing need to understand how to make reservoir investments more effective.

3.2. Introduction

Food demand in sub-Saharan Africa is set to triple by 2050 due to ongoing rapid growth in population and per capita income (van Ittersum et al., 2016). At the same time, agricultural expansion is a driving cause of natural vegetation and biodiversity loss leading to calls to prioritise closing yield gaps over further land conversion (Cunningham et al., 2013; Foley et al., 2011). Irrigation in Africa is considered one of the more promising options for boosting food production because of widespread water constraints to production (Mueller et al., 2012) and higher yields on irrigated compared to rainfed farmland (Xie et al., 2014; You et al., 2011).

The Alliance for a Green Revolution in Africa is advocating a shift in smallholder production towards irrigated systems that enable farmers to produce fresh vegetables and other market crops (AGRA, 2017) while countries across Africa are prioritizing irrigation investments under Pillar 1 of the Comprehensive Africa Agriculture Development Programme. About 70% of Africa’s farmers are estimated to be smallholders (Deininger and Byerlee, 2012). Yet little is known about small-scale irrigation activities. Better information on where irrigated farmland exists could be used to improve estimates of irrigation supply and demand (Cai and Rosegrant, 2002; Wisser et al., 2008), predict and help close gaps in water and food supplies, and be used as input to environmental impact assessments related to land use and agriculture.

In the West African Volta basin, construction of small, community-managed

reservoirs has been advocated over the last few decades to reduce seasonal agricultural water shortages (ADB et al., 2007; Douxchamps et al., 2014; Lemoalle and De Condappa, 2009; Venot and Krishnan, 2011). While their potential to provide multiple benefits and empower communities to increase food production is recognised in national development plans (CPESDP, 2017) and much discussed in scientific literature (Douxchamps et al., 2014; Lemoalle and De Condappa, 2009; Wisser et al., 2010), it is unclear to what extent smaller reservoirs are successful in achieving these aims (Katic et al., 2014; Namara et al., 2010). Data on individual reservoir agricultural uses and crop productivity in the Volta basin show that irrigated crop production, comprising mainly rice and market vegetables, is well below potential (Faulkner et al., 2008; Fowe et al., 2015; Mdemu et al., 2009; Poussin et al., 2015). A study of 126 reservoirs in Upper East Ghana found that only 42% were used for irrigation (Birner et al., 2010), while research at two reservoirs in the same region found that less than 30% of the irrigable areas were in use (Wekem, 2013).

The Global Map of Irrigation Areas (GMIA) shows areas equipped for irrigation and actually irrigated at ~10 km^2 resolution, based on official sub-national spatially explicit records (Siebert et al., 2013). GMIA data indicates that 92% of areas equipped for irrigation are actually irrigated in the Volta basin, equating to 40,436 ha, of which 87% is irrigated with surface water. Several other global datasets on irrigated cropland datasets have been created, also drawing on official irrigated area records. These include the Monthly Irrigated and Rainfed Crop Areas in 2000 (MIRCA2000) (Portmann et al., 2010), and FAO's Global Agro-Ecological Zones project, each mapping irrigated area by crop type for the year 2000. Yet official records are likely to omit information on small and unplanned (*i.e.* irrigation outside of built irrigation infrastructure) irrigated areas because of difficultly collecting data on these. With over 1100 small and medium sized reservoirs in the Volta basin (Jones et al., 2017), the combined documented and undocumented irrigation activity around these reservoirs may make a significant contribution to overall irrigated crop extent.

Data on irrigation extents at individual reservoirs is not readily available in the Volta basin, with the exception of a handful of reservoirs where case studies have occurred, e.g. (Faulkner et al., 2008; Mdemu et al., 2009; Poussin et al., 2015). Lemoalle and de Condappa (2010) estimate 10,000 ha of irrigation is dry season vegetation production around small reservoirs, though the source of this estimate is not provided. Since reservoirs are numerous, collecting data on irrigated cropland through ground studies is time-consuming and resource intensive. The resolution of global irrigation datasets is too coarse to detect smallholder irrigation in the Volta basin, where farms are generally <2 ha (Deininger and Byerlee, 2012) and individual plots even smaller. Previous studies classifying seasonal crop extents tend to focus on large monocropped fields, such as the rice paddies of North-East Asia (Dong et al., 2016) and wheat or rice fields in the United States (Deines et al., 2017). Smallholder irrigation systems in the Volta basin can have a high crop species diversity and small field sizes, and techniques for mapping these systems are underdeveloped.

Dry season irrigated areas may be used to grow crops all year round, or may be subject to seasonal changes in land use where surface water or riparian vegetation in the rainy season gives way to dry season irrigated cropland. Some areas will have transitional irrigation fields that move from year to year adjacent to naturally fluctuating waterlines. In the Volta basin, the dry season extends for 4-8 months of the year, increasing in length along a south to north gradient. Irrigation can be assumed to occur where annual crops grow during this period, when precipitation is insufficient to support crop growth. This crop growth depends on photosynthesis, the process of converting water, energy and carbon dioxide into carbohydrate and oxygen. The photosynthesis process increases chlorophyll content in plant leaves. Chlorophyll absorbs high levels of red and blue light and reflects high levels of near infrared (NIR) light (Jensen, 2007), and as such plants can be detected by comparing the amount of light in these wavelengths reflected from different land covers,

opening up opportunities for remote detection of irrigation.

Many papers have mapped seasonal irrigation extents at local or regional scales using satellite imagery, with mixed success. Techniques include classifying crops at each timestep in the analysis using supervised classification (Beltrán and Belmonte, 2001; Martínez-Casasnovas et al., 2005), developing classification rules based on fluctuations in greenness (MacDonald and Hall, 1980; Massey et al., 2017; Wardlow and Egbert, 2008), combining data from vegetation and soil moisture indices (Xie et al., 2017), and integration of vegetation indices and ancillary data such as climate and national crop statistics (Salmon et al., 2015). Some of the most promising results for distinguishing irrigated cropland from other land use types are associated with use of vegetation indices (Salmon et al., 2015; Xiong et al., 2017).

The Normalised Difference Vegetation Index (NDVI) is an example of an index applied to multispectral imagery to enhance areas reflecting high levels of NIR and low levels of red light, such as vegetation, and suppress areas reflecting high levels of both near infrared and red light, such as soil (Rouse et al., 1973). The main limitation of NDVI is it becomes saturated with canopy density and performance is weakened as bare ground cover increases (Gao, 1996). NDVI is also sensitive to soil moisture (Engstrom et al., 2008), increasing with soil moisture over a range of land types including cropland (Chen et al., 2014).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \tag{5}$$

Xiong *et al.* (2017) successfully used MODIS NDVI to classify irrigated and rainfed cropland at 250 m resolution over Africa for multiple years, with overall accuracies of ~95%. However, Massey *et al.* (2017) were unable to separate irrigated from rainfed cropland in the USA using time-series MODIS NDVI analyses, because of overlap in the mean and

standard deviation in NDVI signal between rainfed and irrigated land for a single crop type. Salmon *et al.* (2015) successfully distinguished irrigated non-paddy cropland, irrigated paddy cropland and rainfed cropland globally, but reported low accuracies over areas with fluctuating irrigation patterns or mixed irrigated and rainfed crops.

In short, previous studies have had some success in mapping irrigated cropland remotely, yet challenges remain in mapping seasonal irrigation on small fields and in mixed-use landscapes which are common to smallholder farming contexts in Africa. Further research may help identify a robust and scalable approach that better suits such contexts.

This chapter tests remote sensing approaches to mapping dry season irrigated cropland in the Volta basin focusing on the use of temporal NDVI trends. Information on irrigated uses of smaller reservoirs is scarce and closing this gap in the Volta basin would be useful to better understand their impact on food production and to improve regional water accounting. I seek to answer two core questions:

(1) How effectively can monthly trends in NDVI from Landsat 8 and Sentinel 2 satellite imagery be used to identify dry season irrigation presence-absence and extent around reservoirs in the Volta basin?

(2) Where are small and medium sized reservoirs in the Volta basin used for dry season irrigation, and what is the total irrigated area?

3.3. Materials and methods

3.3.1. Data

3.3.1.1. Landsat 8 OLI and Sentinel 2 MSI imagery

A total of 574 Landsat 8 Operational Land Imager (OLI) images (corresponding to paths 192, 193, 194, 195, 196, 197) and 4105 Sentinel 2 Multi-Spectral Instrument (MSI) images were sourced from and processed in Google Earth Engine (Gorelick et al., 2017). The spatial resolution of visible and near-infrared bands from these imagery sources is 30 meters and 10 meters respectively. Images spanned the period 01-05-2016 to 01-04-2017 and covered the entire 400,000 km^2 Volta basin.

I used atmospherically corrected Landsat 8 OLI imagery processed to surface reflectance, available in Google Earth Engine. Atmospheric correction is performed by U.S. Geological Survey, using image data and ancillary temperature, water vapour, aerosol and ozone data and based on radiative transfer processes (Vermote et al., 2016)

Surface reflectance imagery from Sentinel 2 MSI were not available in Google Earth Engine at the time of analysis, and therefore Top of Atmosphere imagery were used. This has the limitation that NDVI signals can be distorted by atmospheric effects (Song et al., 2001), yet using this imagery allows for comparisons of image utility as currently provided in Google Earth Engine.

3.3.1.2. Irrigated cropland training and validation data

I collected land use samples for five classes: irrigated cropland, rainfed cropland, non-riparian non-cropland, riparian non-cropland, and water, for use in land use classification training and validation. These five land use classes were selected for the purpose of distinguishing land use types whose spectral signatures could be confused with irrigated cropland. Samples comprised ground data and areas digitised from high resolution imagery. Ground data samples were collected during fieldwork in April and December

2016, and included 40 samples across irrigated, rainfed and riparian land uses collected around four reservoirs in Centre-Est Burkina Faso and Upper-East Ghana.

To augment the ground data, validation samples across all five land use classes were collected from very high resolution imagery available in Google Earth from across the Volta basin. I used imagery available from the dry season, November to April, from 2013 to 2016. Multiple years were used to accommodate data gaps in the Google Earth image archive, however most of the imagery used were from 2016, consistent with the ground data. Random stratified sampling was used to generate boundaries within which to collect these samples, to ensure samples were collected from areas proximate to reservoirs and across the basin's range of climate and hydrological zones. The sampling boundaries were defined by making 1 km buffers around all Volta basin reservoir extents and, within these buffers, randomly generating 200 circular plots of 100 m diameter such that at least one plot was in each distinct climate and hydrology zone (moisture bins, described below) that contained reservoirs. For each plot, I digitised visible land uses. I excluded validation samples where the land use could not be determined with a high level of confidence, e.g. due to cloud-covered imagery or ambiguity between irrigated cropland and riparian land uses.

Overall I collected 225 validation samples across the Volta basin, comprising 43 from irrigated cropland, 61 samples from rainfed cropland, 21 from riparian, 93 from non-riparian other (including forest, grassland, urban, road) and 7 from water. Of these samples, 70% (158) were used to train and 30% (67) to validate each classification map.

3.3.1.3. Reservoir irrigation status reference data

Reservoir irrigation status was determined for all Volta basin reservoirs estimated to hold <10 Mm^3 water and therefore considered small or medium in size, based on analyses of reservoir sizes conducted by Jones et al. (2018). Irrigated cropland around

these 1155 reservoirs was identified from very high resolution imagery acquired by WorldView-2, QuickBird, SPOT and IKONOS sensors, available through Google Earth Pro. For each reservoir, I manually searched for evidence of cropland (tillage lines, field boundaries) adjacent to the reservoir edge or along the immediate downstream river that was at least partially green during the dry season (November to April for most of the basin) using the most recent high resolution imagery in the Google Earth Pro image archive. Imagery used in the analysis was acquired between February 2011 and February 2018, with most of the imagery acquired in 2016. I excluded 27 data points where the most recent imagery available dated pre-2011 or where the status of irrigation could not be reliably determined e.g. due to poor image quality. For the remaining 1128 reservoirs, I recorded:

- Irrigation presence-absence upstream of the reservoir;
- Irrigation presence-absence downstream of the reservoir;
- Presence-absence of irrigation canals (linear channels downstream of the dam wall identifiable on imagery);
- Image acquisition date.

The same imagery was used to digitise irrigated cropland extent. Riparian vegetation was sometimes difficult to distinguish from irrigated cropland since both can be visibly green during the dry season. I used field boundaries, canal infrastructure and tillage lines as further indicators of irrigated cropland, and dense tree cover as indicators of riparian vegetation or woodland areas (see, for example, Figure 11). At some reservoirs, the irrigation extended into areas where imagery was acquired on different dates. In addition to the data points discarded at the irrigation presence-absence step, irrigation extent was not digitised at a further six sites due to this inconsistent image coverage. The resultant datasets on irrigation activity and extents are available for download at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/1BG7VL&ver

sion=DRAFT&faces-redirect=true.

Figure 11: Irrigated cropland downstream of a reservoir. In this example, linear field boundaries and canal infrastructure helped distinguish irrigated cropland from riparian vegetation and other land covers.

3.3.2. Analysis

3.3.2.1. Processing satellite imagery

Landsat 8 OLI and Sentinel 2 MSI imagery include a quality band showing which pixels are potentially cloud covered. I applied a cloud mask to all images before generating indices, whereby pixels with cloud cover were filtered out of the analysis. Removing cloud covered pixels means they can no longer interfere with the band ratio calculations but nonetheless leaves gaps in the imagery, and may result in small underestimations of irrigated area. NDVI were computed using bands 4 and 5 on Landsat 8 OLI imagery and bands 4 and 8 on Sentinel 2 MSI imagery. MNDWI were computed using bands 3 and 6 on Landsat OLI imagery and bands 3 and 11 on Sentinel 2 MSI imagery.

3.3.2.2. Classifying irrigated cropland from NDVI imagery

I tested three approaches to using NDVI time-series imagery to classify dry

season irrigated cropland around reservoirs: Approach 1) identifying areas where NDVI is relatively high locally, e.g. in the top 75th percentile, during the late dry season when NDVI from non-irrigated vegetation is at its lowest; Approach 2) applying a supervised classification with annual and dry season median NDVI and MNDWI, and values for all image bands as inputs; Approach 3) analyzing changes in NDVI signals through the dry season.

For each of these, the dry season was assumed to cover start of November to end of April. Late dry season cropping months refers to the period when crops are most likely to be mid or end stage development and hence green, and was assumed to cover the period start of February to end of April.

Approach 1: Contrast in dry season NDVI values across soil moisture bins in late dry season

Moisture content of vegetation around reservoirs depends not only on irrigation but also on precipitation, subsurface flow and evapotranspiration rates. The rainfall and temperature gradient over the Volta basin means that NDVI values over vegetated areas will be inflated as we move from the drier, warmer north to the humid, cooler south part of the basin, due to climate differentiation. Meanwhile, higher areas will tend to have less surface or subsurface moisture than lower areas, since water flows downhill. Therefore we can expect the background (non-irrigated) NDVI signal to always be relatively high in areas of low elevation (depressions, valleys) compared to irrigated areas, and the contrast to increase as water becomes scarce.

To control for the effects of climate and topography on moisture availability, I separated the Volta basin into potential soil moisture bins using the topographic wetness index and mean annual precipitation levels. The topographic wetness index combines local upslope area with the degree of slope and is used to quantify the effects of topography on hydrological processes (Sørensen et al., 2006). I computed the topographic wetness index

using WaterWorld V2 (Mulligan, 2013) and derived mean annual precipitation from WorldClim V2 (Fick and Hijmans, 2017) data. I made moisture bins by stratifying mean annual precipitation into 200 mm wide classes for the range 322 - 1778 mm per year (i.e. <400mm, 400-599 mm, 600-799 mm,...) and the topographic wetness index into three classes using the mean and standard deviation (< (mean - 1 SD), (mean - 1 SD) to (mean + 1 SD), > (mean+1 SD), then combining these datasets to give 24 unique moisture "bins" (see Figure 12).

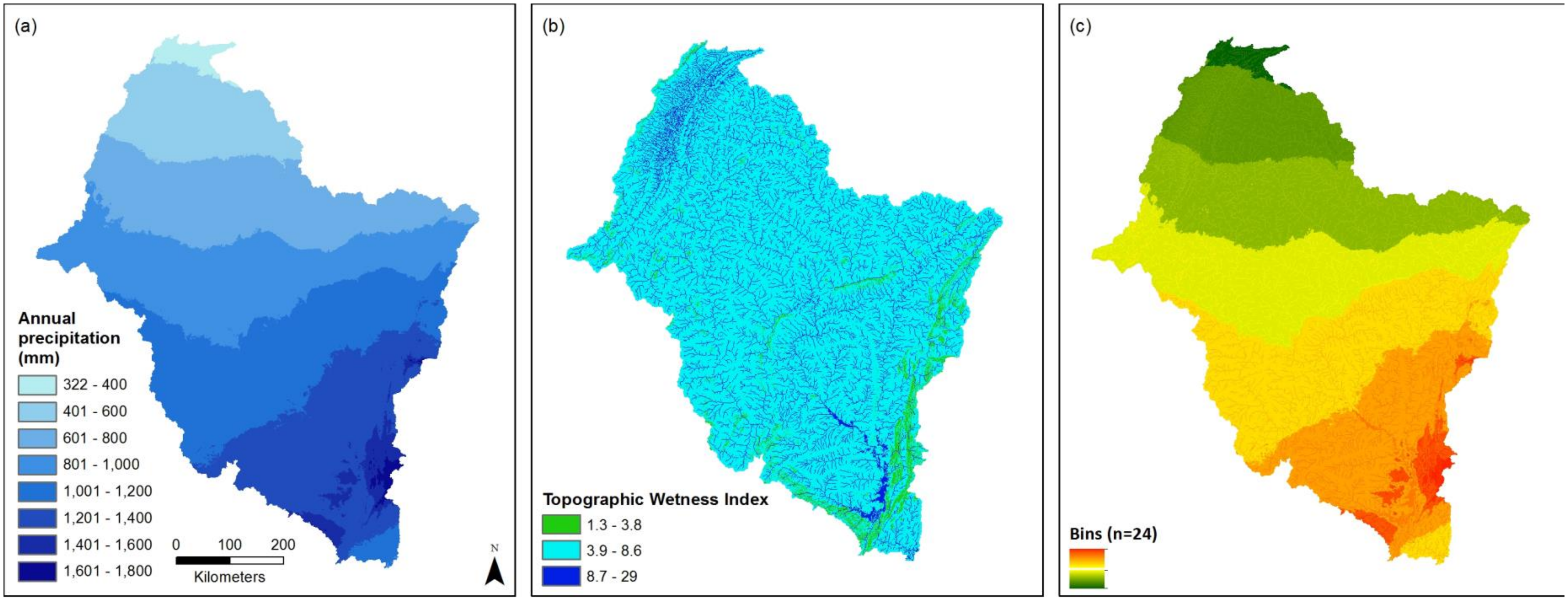


Figure 12: (a) Annual precipitation, (b) topographic wetness index , and (c) unique moisture bins used in the NDVI analysis.

The moisture bins were imported into Google Earth Engine (Gorelick et al., 2017) and subsequent analysis conducted in this platform, using the online code editor. First, I created a tree mask whereby, within each moisture bin, pixels that were in the highest 75th percentile NDVI for more than 80% of the year (excluding months with no data due to cloud cover) were masked out. Next, within each moisture bin, I identified pixels that were in the highest 75th percentile NDVI for at least one month (33%) of the late dry season and classified these pixels as irrigated. The decision to use a one month cut off was based on analysis of percentage of months pixels were in the highest 75th percentile of NDVI in the late dry season across all five classes in the validation dataset (Figure 13). Analysis of distributions showed 77% of observed irrigated pixels were in the highest 75th percentile for at least one month while this was the case for only 29% of observed non-irrigated pixels.

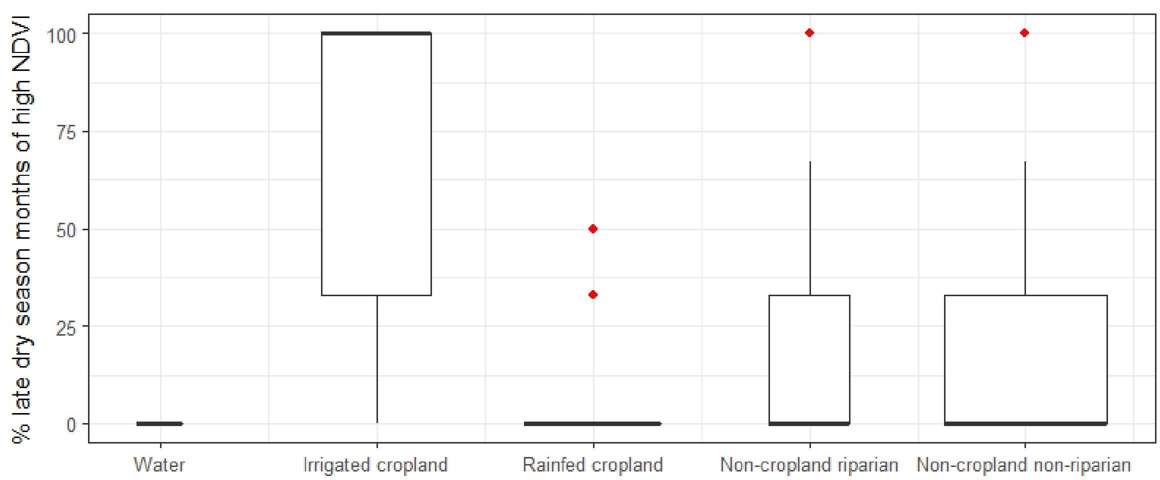


Figure 13: Mean percentage of late dry season months (Feb-Apr) where the median NDVI value was in the highest 75th percentile within each moisture bin across five land use classes, based on analysis of validation data (n=225).

Approach 2: Supervised classification using CART

Incorporating pixel-level differences in moisture levels and reflection values across all image bands may improve the accuracy of irrigated crop classification, relative to Approach 1, since this provides more information on the spectral characteristics of each land use class. Supervised classification methods use an algorithm, such as the Minimum

Distance, Nearest Neighbour or Maximum Likelihood, to classify trained pixels across the full extent of an image (Jensen, 2007). These algorithms work by comparing each pixel's spectral characteristics to those of each of the land cover classes in the training areas, and using logical rules to assign pixels to one of the classes.

I used a Classification and Regression Tree (CART) supervised classifier with the following inputs:

- Median value of visible and infrared bands, to capture spectral differences between irrigated and non-irrigated land.
- Median monthly MNDWI across the year, to capture differences in moisture levels between irrigated and non-irrigated land.
- Median monthly MNDWI across the late dry season, to capture differences in moisture levels between irrigated and non-irrigated land which should be accentuated in the dry season when background moisture levels are lowest.
- Median monthly NDVI across the year, to capture differences in vegetation cover between irrigated and non-irrigated land.
- Median monthly NDVI across the late dry season, to capture differences in vegetation cover between irrigated and non-irrigated land which should be accentuated in the dry season when crops are in the mid to late growth stage and therefore relatively dense and green.
- Standard deviation in median monthly late dry season NDVI, to capture fluctuations in vegetation cover which should be relatively high over irrigated areas compared to non-irrigated areas during the late dry season when crops are in the mid to late growth stage.
- Sum of median monthly late dry season NDVI, to capture areas with

continuous vegetation and high NDVI signals during the late dry season which should be more common in irrigated areas compared to non-irrigated areas when crops are in the mid to late growth stage.

- Percentage of months in the year a pixel is in highest 75th percentile NDVI, separating pixels by moisture bin, to capture differences in the frequency of high NDVI signals between irrigated and non-irrigated land.
- Percentage of months in the late dry season a pixel is in highest 75th percentile NDVI, separating pixels by moisture bin, to capture differences in the frequency of high NDVI signals between irrigated and non-irrigated land which should be accentuated in the late dry season when crops are in the mid to late growth stage.

The CART classifier was applied in Google Earth Engine. Of the 225 land use validation samples, 70% were used to train and 30% were used to validate the CART classifier.

Approach 3: Seasonal change detection

We can expect trends in NDVI signals over irrigated areas to be notably different to other vegetation types over the course of a dry season. Irrigated crops should have an increasing NDVI over part of the dry season as plants grow, while other land covers should have a stable or declining NDVI as vegetation remains relatively unchanged (evergreen forests, riparian vegetation, perennial crops, urban areas, water), dries out (deciduous forests, natural grassland), or is temporarily removed (rainfed cropland). Therefore exploiting the temporal pattern in NDVI through the dry season may enable irrigated land to be distinguished from other land types.

Indeed for the Volta basin, there was a rise in NDVI over known irrigated areas between December and March (the late dry season) within most moisture bins - regions

defined by moisture retention characteristics - but a declining signal was evident in bin 7 (Figure 14). On inspection, 8 of the 10 irrigated cropland samples in bin 7 were from ground data collected in April 2016, and it is possible no irrigation occurred at some of these plots in the 2016-17 season due to the transitory nature of irrigation activities; however this could not be confirmed.

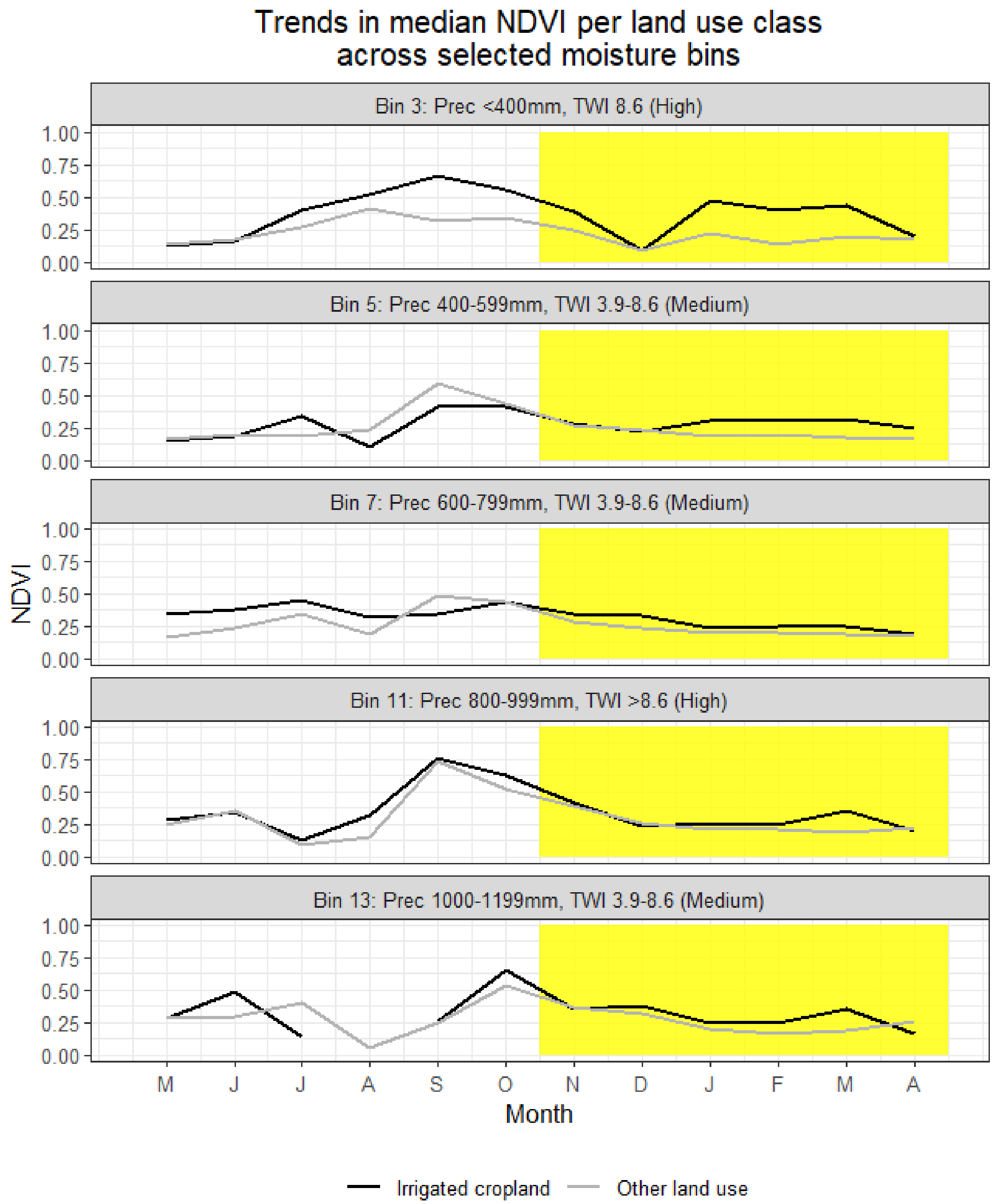


Figure 14: Trends in median NDVI per land use class across selected moisture bins within the Volta basin from May 2016 to April 2017, based on land use samples in the validation dataset (n=225). Dry season months are shaded yellow.

To distinguish irrigated areas based on dry season NDVI trends, I identified pixels where the NDVI increased between the middle and end of the dry season cropping period, i.e. between December-January and February-March. I applied a water mask to eliminate confusion with water pixels, by classifying all pixels with MNDWI values >-0.2 as water.

This water threshold was selected based on previous research into optimal results for reservoir water detection in the Volta basin (Jones et al., 2017). Pixels with a positive change in mean NDVI between December-January and the succeeding February-March were classified as irrigated cropland.

3.3.2.3. Validation of classification results

I compared classification accuracies by computing error matrices. These matrices compare image-based classifications on one axis with reference classifications on the other over a number of sample areas, making it possible to calculate the ratio of correctly classified samples to the total number of samples (Congalton and Green, 2009).

3.3.2.4. Automatic determination of reservoir irrigation status

Identifying dry season irrigated cropland in close proximity to a reservoir can be used to determine whether or not a reservoir is used for irrigation. Plots that are 100 m or further from the reservoir, and therefore impractical to irrigate using buckets, may be irrigated with water piped from the reservoir, or from another water source such as a river. The maximum distance from a reservoir that reservoir water is used for irrigation will vary depending on local infrastructure and means of water transportation. It was assumed in this study that most irrigation is <2km from a reservoir edge or dam wall. Clusters of irrigated pixels within 2km of a reservoir dam wall or edge at its maximum extent were extracted using the connectedPixelCount and connectedComponents algorithms in Google Earth Engine, based on land use classified using the classification approach with the highest irrigated cropland mapping accuracy.

To minimise commission errors in the extracted irrigated areas dataset, I removed clusters containing fewer than 5 Landsat 8 OLI imagery pixels (~0.5 ha). All reservoirs that still had irrigated cropland within 2 km were classified as for “Irrigation use” and the irrigated areas summed together to estimate their extents, while other reservoirs were classified as

having “No irrigation use”. Estimates of irrigation status and extent were compared against the reference data.

3.4. Results

3.4.1. Classification accuracies

Using Approach 1, irrigated areas were distinguished from other dry season land uses with an overall accuracy of 86% using Landsat 8 OLI or Sentinel 2 MSI imagery. However, this masks high commission error rates for the irrigated cropland class (Table 7).

Table 7: Confusion matrix for two land use classes, produced by comparing imagery classified using Approach 1 against validation data.

	Classified irrigated cropland	Classified non-irrigated	Omission error rate	Commission error rate	Mapping accuracy
Landsat 8 OLI					
Validation irrigated cropland	44	1	2%	74%	98%
Validation non-irrigated	124	737	14%	0%	86%
Sentinel 2 MSI					
Validation irrigated cropland	353	1	0%	76%	100%
Validation non-irrigated	1106	6495	15%	0%	85%

Approach 2 achieved a higher overall accuracy of 95% with Landsat 8 OLI and 96% with Sentinel 2 OLI when classifying land use into two classes. However this is in large part due to high classification accuracy for the non-irrigated class while commission and omission errors for irrigated cropland were 48%-69% (Table 8).

Table 8: Confusion matrix for two land use classes, produced by comparing imagery classified using Approach 2 against validation data.

	Classified irrigated cropland	Classified non-irrigated	Omission error rate	Commission error rate	Mapping accuracy
Landsat 8 OLI					

	Classified irrigated cropland	Classified non-irrigated	Omission error rate	Commission error rate	Mapping accuracy
Validation irrigated cropland	14	31	69%	48%	31%
Validation non-irrigated	13	843	2%	4%	98%
Sentinel 2 MSI					
Validation irrigated cropland	153	201	57%	50%	43%
Validation non-irrigated	155	7446	2%	3%	98%

Approach 2 produced a slightly lower overall accuracy of 87% using five land use classes, based on results from Landsat 8 OLI (Table 9). The confusion matrix shows that for irrigated cropland, the primary source of error is confusion with riparian land and non-riparian other areas (e.g. forest and savanna).

Table 9: Confusion matrix for five land use classes, produced by comparing Landsat 8 OLI imagery classified using Approach 2 against validation data.

	Classified irrigated cropland	Classified rainfed cropland	Classified riparian, non-cropland	Classified non-riparian, other	Classified water	Omission error rate	Commission error rate	Mapping accuracy
Validation irrigated cropland	11	0	3	0	0	21%	67%	79%
Validation rainfed cropland	2	62	41	41	0	58%	32%	42%
Validation riparian	10	3	11	4	6	68%	86%	32%
Validation non-riparian other	10	26	24	113	9	38%	28%	62%
Validation water	0	0	0	0	1026	0%	1%	100%

Approach 3 yielded an overall accuracy of 62% for Landsat 8 OLI and 75% for

Sentinel 2 MSI, with high commission and omission errors for irrigated cropland (Table 10).

Table 10: Confusion matrix for two land use classes, produced by comparing Landsat 8 OLI imagery classified using Approach 3 against validation data.

	Classified irrigated cropland	Classified non-irrigated	Omission error rate	Commission error rate	Mapping accuracy
Landsat 8 OLI					
Validation irrigated cropland	17	26	60%	78%	40%
Validation non-irrigated	224	119	35%	10%	65%
Sentinel 2 MSI					
Validation irrigated cropland	133	259	66%	82%	34%
Validation non-irrigated	602	2507	19%	9%	81%

For the first two approaches, there was only a marginal difference between overall classification accuracy using Landsat 8 versus Sentinel 2 imagery, while for the third approach overall accuracy was 15% higher using Sentinel 2. Mapping accuracies for irrigated cropland were 2% and 12% higher using Sentinel 2 for Approach 1 and Approach 2 respectively, while the inverse was true for Approach 3 where irrigated cropland mapping accuracy was 6% higher using Landsat 8. The best performing method in terms of mapping accuracy (100%) was achieved using Sentinel 2 imagery and Approach 1, although this method is subject to high rates of commission error.

3.4.2. Visual interpretation of classification results

Inspection of two-class classification results shows that many small patches were erroneously classified as irrigated cropland across all approaches, and particularly using Approach 1 and Sentinel 2 imagery (see for example Figure 15).

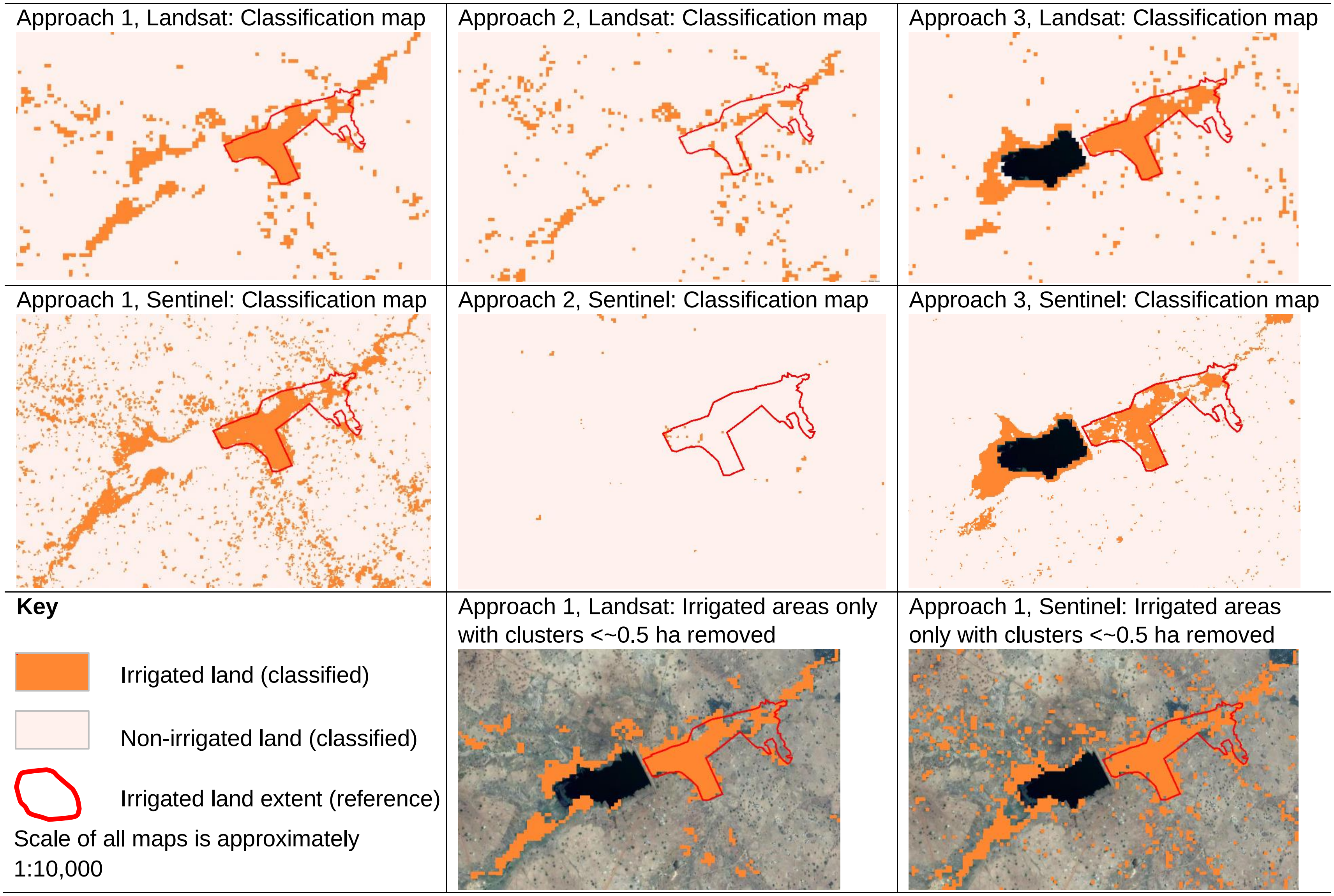


Figure 15: Irrigated and non-irrigated land classified at Binaba reservoir (10.7798N, 0.47777W), overlaid on high resolution satellite imagery (from CNES / Airbus) available in Google Earth Engine.

3.4.3. Reservoir irrigation status

Data on irrigation status collected from Google Earth Pro imagery show that 46% (537) of reservoirs <10 Mm^3 are used for irrigation in the Volta basin. Irrigation is more common at reservoirs in the northern two-thirds of the basin (Figure 16). Crops are irrigated downstream at 453 reservoirs, while at 364 reservoirs crops are also or exclusively irrigated upstream around the reservoir edge. Irrigation canals are present at 151 (28%) of the reservoirs where irrigation occurs, and at a further 7 reservoirs where no irrigation was detected. The latter reservoirs may indicate reservoirs where canal infrastructure is broken or blocked, impeding irrigation. The total irrigated area at small and medium reservoirs is 5588 ha with a mean irrigated area of 10.6 ha per reservoir. Irrigated area varies with reservoir size: at small (<1 Mm^3) reservoirs mean irrigated area is 5.5 ha while at medium size reservoirs (1-10 Mm^3) this increases to 33.5 ha. The total irrigated area upstream of reservoirs is 3028 ha, larger than the total downstream irrigated area (2593 ha). On average, irrigated cropland area located upstream of a reservoir is 25% larger than the downstream irrigated area.

I compare estimates of reservoir irrigation status and extent against reference (Google Earth Pro) data for Approach 1 only, since this showed the highest overall classification mapping accuracy. Using this approach, Landsat 8 OLI and Sentinel 2 MSI derived irrigated cropland maps both indicate *all* reservoirs are used for irrigation based on detection of irrigated areas within 2km of a reservoir edge. This significant discrepancy can be explained by the high commission errors for the irrigated cropland class under Approach 1, and shows that errors remain high even after small clusters of irrigated pixels are removed.

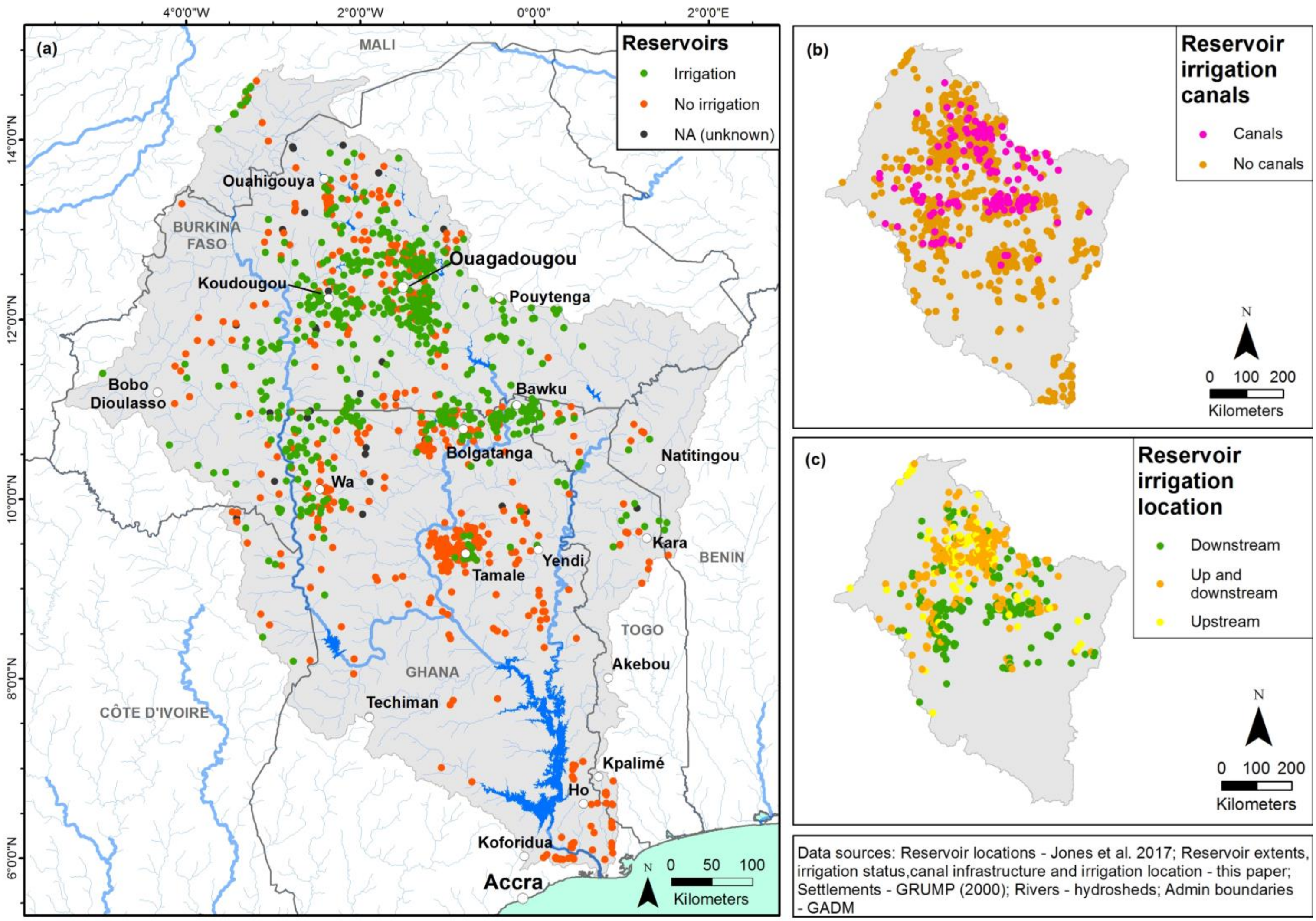


Figure 16: Distribution of (a) irrigation and (b) canal infrastructure at small and medium sized reservoirs in the Volta basin (n=1155), and (c) irrigated cropland location at reservoirs used for irrigation (n=537). Reservoirs whose irrigation status is 'NA (unknown)' (n=27) are those at which the current irrigation status could not be reliably determined.

There were very large over-estimates in the irrigated area for estimates derived from Approach 1 classification maps. In contrast to reference data, deriving irrigated cropland area within 2km of each reservoir from classification maps puts the total irrigated area at between 423,239 and 507,781 ha with a mean of 796-955 ha per reservoir. Root mean square errors in irrigated area estimates are 1033 – 1190 ha with mean absolute percentage errors of over 140,000% (Table 11). The very high percentage errors in irrigated area estimates arise because there are many small reservoirs with observed irrigated areas of <1 ha but which have estimated irrigated areas of between 3.4 and 2844 ha. At the 101 reservoirs where the mean absolute percentage error for Landsat 8 based irrigated area estimates is >100,000%, the mean observed irrigated area size is 0.5 ha compared to mean estimated areas of 1455 ha using Landsat 8 and 1416 ha using Sentinel 2. Excluding reservoirs with irrigated areas < 1 ha brings the mean absolute percentage errors down to near 20,000%, while excluding irrigated areas < 5 ha brings these error measures down to below 8000%. Nonetheless these error rates remain very high and highlight the confusion between irrigated cropland and other land use classes in the classification maps.

Table 11: Estimates of irrigated cropland area around small and medium sized reservoirs used for irrigation, for which reference data on irrigated area were available (n=528).

Source data	Total irrigated area (ha)	Mean irrigated area per reservoir (ha)	Standard deviation (ha)	Mean square error	Root mean square error (ha)	Mean absolute percentage error (%)
Landsat 8-derived classification (Approach 1)	423,239	795.6	671.6	1,067,563	1,033	143,946
Sentinel 2-derived classification (Approach 1)	507,781	954.5	582.8	1,230,497	1,109	150,603
Reference (Google Earth)	5,588	10.6	18.3	-	-	-

3.5. Discussion

Results show that, while automated approaches for mapping reservoir irrigated cropland tested in this paper showed promise, it was not possible to reliably detect or measure the extent of irrigated cropland due to confusion between irrigated cropland and other land use classes. However, the study demonstrates that manual approaches using publically available data and tools can readily be used to assess reservoir impacts on dry season irrigated cropland extent. Irrigation uptake in the Volta basin is relatively low, with over half of small and medium sized reservoirs not used for irrigation. This information has implications for future reservoir investments.

3.5.1. Time-series NDVI of limited use for identifying reservoir irrigation status

Classifying dry season irrigated cropland based on NDVI of Landsat 8 OLI or Sentinel 2 MSI imagery showed promising results notably based on the first approach tested, where mapping (producer) accuracies for the irrigated cropland class were 98-100% and overall accuracy above 86%. These accuracies are comparable with previous studies. However, the high overall and mapping accuracies mask the extent of commission errors which for Approach 1, were in the range 74-76%. Results show these high commission rates render large over-estimates both in the number of reservoirs that are used for irrigation, and in the size of the irrigated area.

Commission errors for the irrigated cropland class arose from confusion with riparian areas and mixed ('Other') land use classes, with the latter including forest and savanna. It is difficult to separate out riparian vegetation because even though river flow is intermittent, subsurface water (that is left as the reservoir area recedes and that leaks from the water body through the soil matrix) will sustain vegetation in the dry season. Grasses and mosses can emerge in the damp areas created where reservoir water recedes through the year, causing an increase in NDVI during the dry season and increasing the likelihood

of misclassification with irrigated cropland for approaches tested in this paper. While confusion between irrigated cropland and evergreen trees was minimised in this paper by masking out pixels with near year-round relatively high NDVI, areas with deciduous trees or woody shrubland are more difficult to deal with. Tree phenology in West Africa savanna may make it challenging to separate deciduous vegetation using NDVI trends because drought resistant traits can lead to late dry season leaf growth (de Bie et al., 1998) which would result in an increase in NDVI during the dry season. Future research to map dry season irrigated cropland in the Volta basin could apply a further discrimination on the basis of the presence of fences or earth walls around irrigated areas, commonly used to prevent livestock trampling crops, or the rectilinear shape of the plots.

Interestingly, classification accuracies were similar for Landsat 8 OLI surface reflectance and Sentinel 2 MSI top of atmosphere imagery. This implies that the lack of surface reflectance imagery for Sentinel 2 does not prohibit useful applications of this imagery for land use classification in Google Earth Engine. Conversely, it may be preventing the benefits of Sentinel 2’s superior imagery resolution (10 m compared to 30 m) from being fully realised.

3.5.2. Manual approaches are a viable alternative

This study found that exploiting imagery in the Google Earth repository and manually digitising irrigated cropland was a practical, effective method of getting data on reservoir irrigation status and extent. This method could be reused in other seasonally dry landscapes to help water managers and irrigation planners monitor irrigation activities. Limitations are that it is time-consuming – approximately 160 hours were required for one person to collect data on irrigation extents for 528 reservoirs - and its reliability depends on the timing of dry season imagery available in the Google Earth repository in relation to the cropping season. Google Earth imagery was not available in the same year and month of the dry season at every reservoir, and dry season cropped areas may not be visibly green

early in the season when crops are short, or late in the season for crops that are already harvested. I used a precautionary approach to delineating dry season irrigation around reservoirs, excluding areas where the irrigation status was uncertain. While this means I am confident that the areas delineated are indeed actively irrigated, the total irrigated area is likely to be slightly underestimated.

3.5.3. Land use reference data challenges

The inconsistency of Google Earth image availability made it challenging to use this as a source of validation and training data in the image classification part of this study. Specifically, 24 of the 200 randomly generated land use sampling areas were discarded because there was no dry season, recent or clear imagery available over these areas. I dealt with this constraint by generating a sufficiently high number of random sample areas that excluding ~10% left enough samples for use in classification. An alternative approach would be to collect training and validation data through additional ground studies or from commercial high-resolution imagery acquired over the region for at least two points in the dry season. However, this can be very costly and is prohibitive to most studies.

3.5.4. Impacts of small and medium sized reservoirs

Results show that nearly half of the reservoirs <10 Mm^3 in the Volta basin are used for irrigation. These reservoirs are concentrated in the central and northern parts of the basin. Of the six Volta basin countries, irrigation uptake relative to the number of reservoirs is highest in Burkina Faso. The relatively low uptake of irrigation at reservoirs in the south of the Volta basin may be because of a coincident lack of canal infrastructure, and because of higher rainfall levels making farmers less reliant on irrigation to produce crops.

There is a notable variation in the extent of irrigated cropland area across reservoirs used for irrigation, with areas ranging from 0.1 to 169 ha, and averaging 10.6 ha. Given the irrigated area varies substantially for reservoirs holding similar volumes of water, this suggests irrigation area is well below potential at some sites, confirming results from

previous studies (Faulkner et al., 2008; Mdemu et al., 2009; Ofosu et al., 2010; Poussin et al., 2015). Together reservoirs used for irrigation support 5588 ha of dry season irrigated cropland. While small, this constitutes a not insignificant 14% of the GMIA estimated total irrigated area in the Volta basin (40,436 ha). It is likely that most of the 5588 ha detected in this study are not in fact included in the GMIA estimate since the latter is derived from official records of areas equipped for irrigation, and therefore total irrigated area in the Volta basin could be nearer 46,000 ha.

3.5.5. Beyond irrigation

Over half of the reservoirs assessed in this study were not used for irrigation, begging the question as to what these reservoirs are used for. Man-made dams have negative impacts on the environment (McCartney, 2009) and their reservoirs are known to increase malaria prevalence among local populations (Boelee et al., 2009; Kibret et al., 2009). There need to be clear benefits to make these interventions justifiable.

One explanation is that reservoirs not used for irrigation serve local livelihoods in other ways. Community-managed reservoirs are often multi-purpose, used for livestock watering, fisheries, domestic and construction use in addition to irrigation (Acheampong et al., 2014; Ayantunde et al., 2018; Douxchamps et al., 2015). Irrigation at reservoirs used by pastoralists or fishers may be avoided by local communities to keep water withdrawals within sustainable limits and avoid conflicts. Nomadic pastoralists in West Africa have centuries-long established corridors that connect perennial surface water sources (Clanet and Ogilvie, 2009) while small-scale fisheries at Volta basin reservoirs provide an important source of nutrients and income to local households (Béné and Russell, 2007). Yet many Volta basin reservoirs are ephemeral (Cecchi et al., 2009; Jones et al., 2017), drying up rapidly after the rainy season ends, so will be of limited use to pastoralists or fishers.

Another explanation is that many of the reservoirs were intended to support irrigation but uptake has not happened or has not been sustained due to insufficient water,

inputs or other factors. This explanation seems more likely given the prevalence of upstream irrigation at reservoirs identified in this and previous (Birner et al., 2010; de Fraiture et al., 2014) studies. Irrigation canals facilitate water access and yet are present at only 14% of small and medium sized reservoirs, making it more difficult for farmers to maximise the benefits of irrigation. Fresh approaches to dam infrastructure planning and maintenance may be needed to ensure factors associated with irrigation adoption are in place, and opportunities for smallholder irrigation are not missed.

3.5.6. Priorities for future research

This study tested three approaches to mapping dry season reservoir-irrigated cropland in the Volta basin, using Landsat 8 OLI and Sentinel 2 MSI imagery. Results might be improved using alternative data sources or classification methods. Subsequent studies could explore the use of Sentinel 2 MSI processed to surface reflectance, or the use of higher resolution imagery from other sensors such as SPOT6 (6m resolution for spectral bands). These high resolution data sources may more successfully distinguish small fields of irrigated cropland. Future research could also try combining spectral analyses with other classification techniques. The approaches tested here showed that, for the Volta basin case, it was difficult to separate small-scale irrigated cropland from natural vegetation classes based on temporal NDVI or other spectral characteristics alone. This is consistent with other studies in landscapes with multiple crops and crop planting schedules, where the relationship between NDVI and irrigation can be complex (Ozdogan et al., 2010). Research from other semi-arid regions has successfully distinguished smallholder irrigated cropland by combining temporal NDVI characteristics and object-based image analysis (Vogels et al., 2019). Future studies could test whether the inclusion of object-based classifiers to exploit features such as field shape or the presence of linear field boundaries could be similarly effective in the Volta basin.

3.6. Conclusion

This paper tested a Google Earth Engine-based approach to mapping dry season irrigation around small and medium reservoirs in the Volta basin, using Landsat 8 OLI and Sentinel 2 MSI imagery and exploiting trends in the Normalised Difference Vegetation Index (NDVI). While promising overall classification accuracies were achieved (in the range 86 – 96%), substantial commission errors for irrigated cropland lead to very high over-estimates for reservoir-irrigated cropland presence and area. Manual approaches using publically available Google Earth Pro imagery were shown to be a viable and practical alternative until such time that methodological advances allow for automated small-scale irrigated cropland detection. Applying a manual approach, this study provides the first comprehensive estimate of irrigation uses and areas associated with small and medium reservoir investments in the Volta basin. Currently, dry season irrigation occurs at 46% of Volta basin's 1155 small and medium size reservoirs, with total irrigated cropland amounting to just 5588 ha. The manual approach used here for monitoring and evaluating the impact of dam investments on irrigated cropping could be readily applied to other regions in Africa and globally, to build an evidence base of the effectiveness of these investments in different contexts. Further research is needed to understand why irrigation adoption rates are relatively low and which factors are conducive to its uptake.

4. Dry season irrigation uptake and sustainability varies with socio-economic and environmental context

Understanding when reservoirs effectively lead to increases in crop production, and the environmental sustainability of this production, is important for identifying pathways to sustainably increasing agricultural production. Results from Chapter 3 show that irrigation is practiced at only 46% of the 1155 small and medium sized reservoirs in the Volta basin and upstream irrigation is common. This chapter i) explores what socio-economic and environmental factors are associated with irrigation presence-absence and location across the Volta basin, drawing on previous studies and qualitative research at case study sites, and ii) compares the environmental sustainability of reservoir irrigated cropland in terms of crop water productivity and identifies factors associated with more sustainable reservoir irrigation systems.

4.1. Abstract

Reservoirs formed by damming minor rivers alleviate the primary resource constraint to dry season food production for smallholder farmers in semi-arid landscapes. Farmers practicing crop irrigation at these reservoirs can significantly boost their household food supplies and revenues from food sales, improving nutrition (SDG 2) and reducing poverty levels (SDG 1). Irrigation is practiced at under half of the 1155 small and medium sized reservoirs in the Volta basin and irrigation outside of the designated irrigation scheme is common. It is unclear why this is the case. This chapter assesses which socio-economic and environmental factors are associated with irrigation presence-absence and location (upstream or downstream) at small and medium sized reservoirs (those holding <10 Mm^3 water) in the Volta basin. Potential factors were selected based on evidence from previous small-scale studies in the region and discussions with local farmers and key stakeholders at four case study sites. The environmental sustainability of dry season irrigation at small and medium sized reservoirs was compared using estimates of reservoir irrigation water

withdrawals per hectare of irrigated cropland. Results show that irrigation uptake is significantly more likely at reservoirs with better water availability, better local market access, greater pressure on local water resources, and where there are marginally fewer human resources available. Prioritizing sites where these factors co-occur in future reservoir investments aimed at boosting crop production is likely to increase the chances of success. Smaller reservoirs (<157,597 m^3) performed best in terms of environmental sustainability outcomes, suggesting there may be sustainability value in favouring investments in smaller reservoirs. Careful upstream land management, diversification of cropping systems and optimizing irrigation schedules to conserve water are likely to further improve the sustainability of reservoir water resource use for food production.

4.2. Introduction

Agricultural production in sub-Saharan Africa is dominated by smallholder farmers (Deininger and Byerlee, 2012), many of whom live in chronic poverty (Beegle et al., 2016) with high food insecurity (Sasson, 2012). Yields in the region are amongst the lowest in the world (Pradhan et al., 2015) and a rapidly expanding population is reducing production per capita (Funk and Brown, 2009). Opening up opportunities for supplemental and dry season irrigation is a promising strategy for achieving increases in food production in areas with variable or low rainfall (Burney et al., 2013; Rockström and Falkenmark, 2015). Irrigation enables production of crops that require high or frequent intake of water and have high nutritional or cash values, such as fruits, vegetables and nuts, with potential to improve local nutrition and household incomes. Increasing smallholder uptake of irrigation is a regional policy priority in sub-Saharan Africa, advocated by the Alliance for a Green Revolution in Africa (AGRA, 2017) and embedded in Pillar 1 of the Comprehensive Africa Agricultural Development Programme.

Decentralised irrigation systems are promoted as investments that use water resources more productively, improving nutritional outcomes, boosting rural development

and reducing income inequality (Burney et al., 2013). Water stored by damming minor rivers to create small, community-managed reservoirs is one such investment for reducing limited access to irrigation water in seasonally dry areas. Globally, the water stored in small reservoirs is considered sufficient to increase cereal production by 35% through supplemental irrigation alone (Wisser et al., 2010), highlighting their enormous potential. Small dams are generally cheaper and quicker to build than large state-managed dams, attractive to governments and donors as a way to avert the social and environmental problems associated with large dam structures and providing a means to support projects in multiple locations with the potential for more distributed development impact. However, evidence is mixed as to whether smaller reservoirs have a lower environmental or social impact than large reservoirs (de Fraiture et al., 2014; Downing, 2010; Kibler and Tullos, 2013; McCartney, 2009; Nkhoma, 2011; Venot and Krishnan, 2011). Research from Malawi reports that small reservoirs encounter many of the same problems that made large reservoirs unpopular, including top-down planning, neglect of local interests, and conflicts over water use (Nkhoma, 2011). Chapter 3 showed that many small and medium sized reservoirs in the Volta basin are not actually used for irrigation, consistent with previous studies (Birner et al., 2010) and calls into question the effectiveness of these investments at increasing smallholder irrigated cropping.

Evidence of low irrigation uptake rates at small and medium sized reservoirs raises the question as to what factors make reservoir investments more likely to succeed in increasing irrigation. Several previous studies have researched this question at local and sub-national levels. Birner et al. (2010) used an econometric analysis to explore possible covariates of irrigation and found that at 126 reservoirs in Upper East Ghana, reservoirs were significantly more likely to be used for irrigation where there was better water availability (e.g. larger reservoir volumes), higher soil quality, and a concrete spillway. Other micro-scale studies point to additional factors that may enable or constrain irrigation

adoption at Volta basin reservoirs. Wekem (2013) found that women, less educated and poorer farmers were less likely to practice dry season irrigation around two reservoirs in Upper East Ghana than their counterparts. Research at five reservoirs in Nord Burkina Faso showed that Peulh farmers were significantly less likely to irrigate than other ethnic groups while larger households or those with larger farm areas were more likely to irrigate than their counterparts (Ayantunde et al., 2018). It is also possible that irrigation is not practiced at some reservoirs in order to resolve conflicts between water users, such as competition between pastoralists and irrigators (Ayantunde et al., 2018; Sally et al., 2011).

Where reservoirs are used for irrigation, irrigated cropping is normally planned downstream of a dam wall and is facilitated with construction of canals that channel and regulate water flow. Downstream irrigation can still occur at Volta basin reservoirs with no canals, with water extracted by motorpump or from shallow ponds, earth canals or wells dug behind the dam wall (Acheampong et al., 2014). Sizeable areas of upstream irrigation at small and medium sized reservoirs were identified in Chapter 3 and are reported in the literature (de Fraiture et al., 2014), where farmers crop along the reservoir's receding waterline and withdraw water with motor pumps or buckets. Given the limited water availability and promotion of agrochemicals by agricultural services as a route to improve yields (Sheahan and Barrett, 2017), upstream irrigation may pollute the water resource and drive water use and management conflicts, e.g. among irrigators, between herders and irrigators, or between fishermen and irrigators.

No previous studies have assessed what factors are associated with irrigation uptake and location at the Volta basin level. In its 2017-2024 rural development plan, Ghana has committed to expanding irrigation across the country through a "One Village, One Dam" initiative (CPESDP, 2017). Meanwhile in its 2016-2020 national development plan, Burkina Faso has committed to increasing investments in dam rehabilitation to 18 per year and construction of new dams to 14 per year by 2020 (PNDES, 2016). While small, community-

managed reservoirs remain a government and donor priority in the Volta basin, stronger evidence is needed regarding what factors are conducive to ensuring these infrastructures have a positive and sustainable impact on irrigated crop production, to guide future investments.

This paper examines what socio-economic and environmental factors are associated with reservoir-irrigation uptake and location (up or downstream) across the Volta basin. It focuses on small and medium sized reservoirs, which are most likely to be community managed and used by smallholder farmers. Principal components analysis (PCA), parametric tests for significant differences (ANOVA, T-test) and spatial overlay analysis were applied to explore how irrigation at these reservoirs varies with selected socio-economic and environmental factors. Environmental sustainability of reservoir-irrigation was compared using dry season irrigated food production extent (ha) and dry season reservoir water loss (m^3). The study addresses the following research questions:

1. To what extent can social, economic and environmental data available across the Volta basin explain variation in irrigation uptake (presence-absence, location) at small and medium sized reservoirs?
2. How environmentally sustainable is irrigated food production at these reservoirs?

Publically available data sources and tools were used where possible so the approach can be readily applied to other geographies.

4.3. Materials and methods

4.3.1. Data

4.3.1.1. Irrigation activities

Information on irrigated cropland presence-absence, irrigated cropland location (up or downstream), and canal infrastructure were mapped from Google Earth imagery,

described in Chapter 3.

4.3.1.2. Covariates

To guide the selection of covariates, I used information gathered through fieldwork and evidenced in previous local studies of factors enabling or constraining irrigation.

Over the course of two fieldwork seasons in April and December 2016, I held farmer focus groups at four community-managed reservoirs used for irrigation. I also conducted semi-structured interviews with 2-3 key stakeholders at each site. These reservoirs included Bidiga and Ladwenda in the Centre-Est region of Burkina Faso, and Binaba and Tanga in the Upper East region of Ghana. Focus groups with 5-10 local crop farmers were used to discuss who uses the reservoir to irrigate, where and what crops are planted, how crops are managed, and end uses of irrigated crops, *i.e.* home consumption or sale (see focus group protocol in Appendix D). The interviews lasted approximately 30 minutes and included local extension officers, dam management committee members and farmer association representatives, who were asked about enablers and constraints to irrigation water access. Ethical approval for these research activities was obtained from King's College London Research Ethics Committee (application number LRS-15/16-2825).

The interviews and focus groups revealed some factors that may limit reservoir water access and use for crop production. For example, land access through tenure or rental, seasonal labour availability, access to agricultural inputs, reservoir water allocation decisions by local committees, and canal infrastructure presence and functionality were identified at all four sites as key factors determining household reservoir water use for irrigation. Canal infrastructure existed at three of the case study reservoirs to facilitate downstream water access, while at Tanga access was via the river and shallow ponds dug downstream of the dam wall. Community members from Binaba, Bidiga and Ladwenda reported that when canals are blocked or break, mobilising the government or the community to make repairs can take many months and lead to a break in irrigation activities.

Upstream of the reservoirs at all sites, I observed reservoir water use for irrigating small plots with water obtained by digging shallow wells, use of buckets or motor pumps. At all the case study sites, focus group participants explained that upstream irrigation is normally unauthorized. An exception was at Ladwenda, where participants clarified that in some specific locations upstream irrigation is authorized by the dam management committee to support families with no or insufficient access to land in the official irrigation scheme. Across the sites, focus group participants agreed upstream irrigation is practiced by those farmers that do not have access to land in the downstream irrigation scheme, indicating land access is a key driver of irrigation location.

Previous studies highlight additional factors that may be important to irrigation uptake (Birner et al., 2010; Wekem, 2013), discussed in the Introduction and detailed in Table 12. Some potentially relevant factors were not tested here due to lack of Volta-wide (e.g. land access) or locally validated (e.g. field size) data. At reservoirs where irrigation occurred, this study tested which of the same factors might explain irrigation location, i.e. upstream or downstream. Maps of each factor are shown in Figure 17.

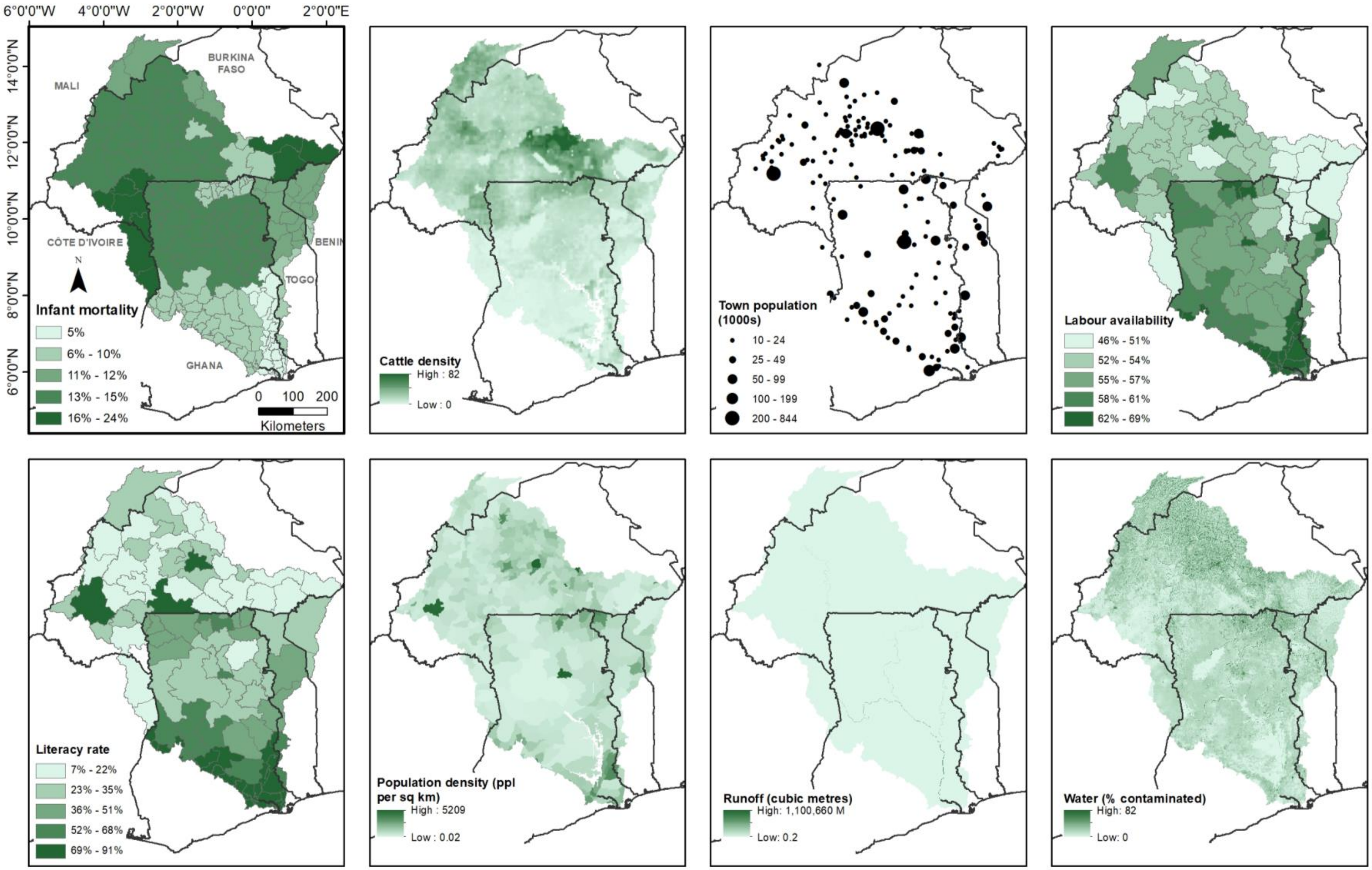
Table 12: Factors that may explain patterns in reservoir use for irrigation across the Volta basin tested in this study, specifying data sources, units and boundaries of analysis.

Factor	Factor type	Justification for inclusion	Direct or proxy data used in this analysis	Units	Boundary of analysis
Household income	Economic	Wekem (2013)	Mean infant mortality rate (deaths for children <5 yrs old, per 1000 live births) as a proxy for poverty level, based on sub-national survey data. Data for Benin (2013), Burkina Faso (2010), Côte d'Ivoire (2010), Ghana (2008), Mali (2013) and Togo (2010) were obtained at admin level 1 from opendataforAfrica.org (accessed 7 August 2018).	Percentage	2km buffer around reservoir extent*
Market access (dam isolation)	Economic	Birner et al. (2010)	Proximity of reservoir to a town of >10,000 inhabitants, based on GRUMP v1 (2000) settlement population size point data (Balk et al., 2006; CIESIN et al., 2011)	Meters	Euclidean distance from center of dam wall to town
			Mean travel time to a city, based on the global map of city accessibility where cities have >50,000 inhabitants or >1,500 inhabitants per km^2 (Weiss et al., 2018)	Minutes	2km buffer around reservoir extent*
			Proximity to a road, based on roads in the Digital Chart of the World (DIVA-GIS, 2018)	Meters	Euclidean distance from centre of dam wall to town
Labour availability	Economic, social	Case study interviews	Mean ratio of adults to children (<15 years old), based on sub-national survey data. Data for Benin (2013), Mali (2008) at admin level 1 and Togo (2010) at admin level 2 were obtained from opendataforAfrica.org (accessed 7 August 2018), while data for Burkina Faso (2006), Côte d'Ivoire (1998) and Ghana (2010) at admin level 2 were obtained from national census data	Percentage	5km buffer around reservoir extent*
Population pressure	Social	Birner et al. (2010), case study interviews	Mean population density, based on the Gridded Population of the World (GPW), v4 dataset for 2015	Persons per square kilometer	2km buffer around reservoir extent*

Factor	Factor type	Justification for inclusion	Direct or proxy data used in this analysis	Units	Boundary of analysis
Livestock density (possibly related to proportion of Peulh (herders) in local population)	Social	Wekem (2013), Ayantunde et al. (2017)	Mean livestock density, based on the Gridded Livestock of the World 2 dataset (Robinson et al., 2014)	Cattle per square kilometer	2km buffer around reservoir extent*
Education level	Social	Wekem (2013)	Mean literacy rate based on sub-national survey data. Data for Benin (2010), Mali (2006) and Togo (2006) at admin level 1 and Côte d'Ivoire (2010) at admin level 2 were obtained from opendataforAfrica.org (accessed 7 August 2018), while data for Burkina Faso (2008) and Ghana (2010) at admin level 2 were respectively obtained from national agricultural survey data via FAO CountryStat and national census data via Ghana Statistical Service**	Percentage	2km buffer around reservoir extent*
Irrigation equipment availability	Technical	Case study interviews	Presence-absence of irrigation canals, systematically obtained from observations of Google Earth imagery (this paper)	1,0	N/A
Soil quality	Biophysical	Birner et al. (2010)	Mean soil organic carbon content, from the global Topsoil Organic Carbon dataset (HWSD V1.1)	Percentage	2km buffer around reservoir extent*
Irrigable land availability		Case study interviews	Perimeter length of reservoir which determines how many plots of land can be immediately adjacent, obtained using the extent of the reservoir surface area in October*** 2017 (corresponding to start or prior to start of dry season cropping for most of the basin) using water detected by analyses of Landsat 8 satellite imagery (MNDWI using band 6, threshold -0.2), based on methods described in Jones et al. 2017.	Meter per cubic meter	N/A
Dry season water availability		Birner et al. (2010), Case study interviews	Reservoir storage capacity obtained using the extent of the reservoir surface area in October*** 2017 using water detected by analyses of Landsat 8 satellite imagery (MNDWI using band 6, threshold -0.2), and applying area-volume relationships, based on methods described in Jones et al. 2017.	Cubic meters	N/A

Factor	Factor type	Justification for inclusion	Direct or proxy data used in this analysis	Units	Boundary of analysis
			Mean annual runoff into reservoir, calculated using WaterWorld V2.	Cubic meters	Calculated at point the main stream inlet meets reservoir
			Mean percentage of months in a year the reservoir is dry, calculated from analyses of Landsat 8 satellite imagery from May 2013 to May 2018 (MNDWI using band 6, threshold -0.2), using methods described in Jones et al. (2017).	Percentage	N/A
Reservoir water quality		Poor water quality may prevent use of water for fisheries or livestock, increasing irrigation use	Percentage of contaminated water at reservoir, calculated using WaterWorld V2.	Percentage	Calculated at point the main stream inlet meets reservoir
Sedimentation rates		Case study interviews	Mean sediment in transportation received by reservoir, calculated using WaterWorld V2.	Tonnes per year	Calculated at point the main stream inlet meets reservoir
			Mean sediment deposited at reservoir, calculated using WaterWorld V2.	Tonnes per year	Calculated at point the main stream inlet meets reservoir
Farm size, land tenure, seed access, fertiliser access, regulations imposed by local water management authority	Social, economic	Wekem (2013, farm size); Case study interviews (other variables)	N/A – none available or globally available data not validated locally	N/A	N/A

* Reservoir extents were obtained through analysis of Landsat 8 satellite imagery from October 2017 (corresponding to start or prior to start of dry season cropping for most of the basin) using water detected by analyses of Landsat 8 satellite imagery (MNDWI using band 6, threshold -0.2), based on methods described in Jones *et al.* (2017). Data from November 2017 were used where no imagery were available from October 2017. No water was detected at 161 reservoirs, and at these reservoirs the buffer was made around the point representing the centre of the dam wall.
** Newer data on literacy rates were available for Benin (2015) and Burkina Faso (2014), however the most recent data for Mali and Togo was 2006 while the year of data obtained from national ministries for Ghana was 2010. The most recent data available between 2006 and 2010 were selected for each country, to reduce the range of years from which data were sourced across the six Volta basin countries.



6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
14°0'0"N
12°0'0"N
10°0'0"N
8°0'0"N
6°0'0"N
MALI
BURKINA FASO
CÔTE D'IVOIRE
BENIN
TOGO
GHANA
N
Infant mortality
5%
6% - 10%
11% - 12%
13% - 15%
16% - 24%
0 100 200
Kilometers
Cattle density
High : 82
Low : 0
Town population (1000s)
10 - 24
25 - 49
50 - 99
100 - 199
200 - 844
Labour availability
46% - 51%
52% - 54%
55% - 57%
58% - 61%
62% - 69%
Literacy rate
7% - 22%
23% - 35%
36% - 51%
52% - 68%
69% - 91%
Population density (ppl per sq km)
High : 5209
Low : 0.02
Runoff (cubic metres)
High: 1,100,660 M
Low: 0.2
Water (% contaminated)
High: 82
Low: 0

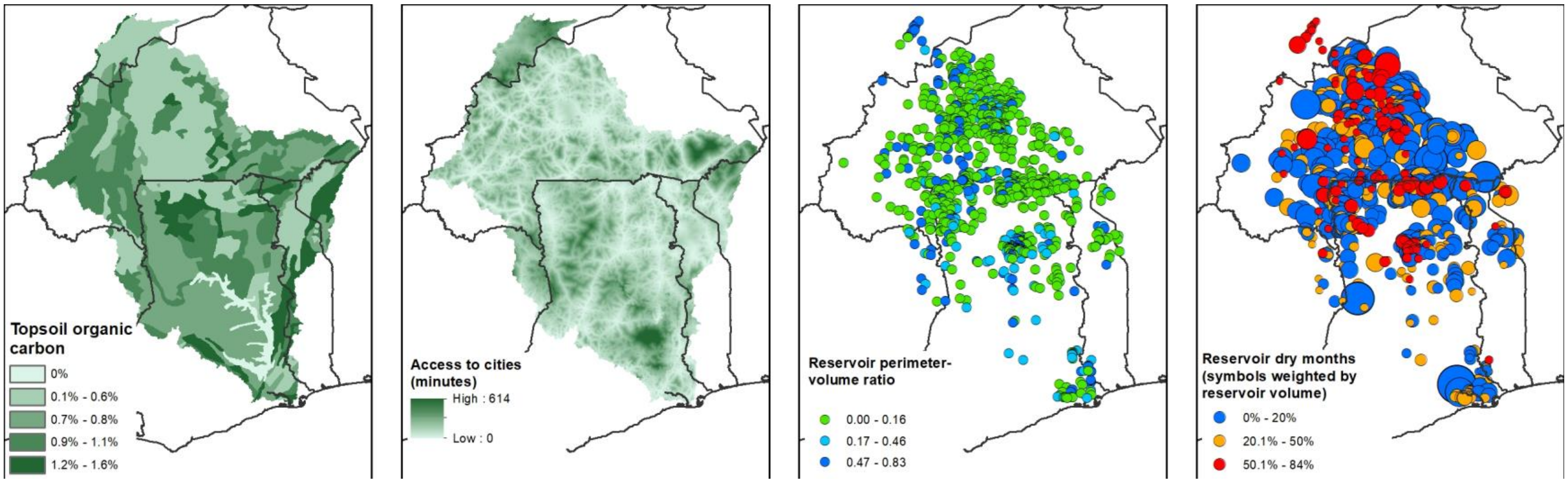


Figure 17: Maps of factors included in the analysis of socio-economic and environmental factors associated with reservoir irrigation patterns.

4.3.1.3. Sustainability indicators

Reservoirs where less water is used to produce more food may be considered more environmentally sustainable. At reservoirs used for irrigation, the sustainability of dry season irrigated crop production was measured in terms of water productivity, based on the ratio of dry season irrigated cropland extent (ha) to dry season reservoir water loss to irrigation (m^3), assuming a six month dry season from November to April. This gives an indication of the water productivity, i.e. the amount of food produced for each unit of water (Cook et al., 2006).

Irrigation extents were digitised from Google Earth imagery at each reservoir, as described in Chapter 3. The mean difference in reservoir maximum and minimum volumes over the dry season of each year from 2013-2018 was used to determine dry season reservoir water loss to irrigation, excluding years where insufficient imagery were available at the start and end of the dry season. Where information on reservoir volume was not available in any of the five years, these reservoirs were excluded from subsequent analyses. Reservoir volumes were determined from Landsat 8 imagery in Google Earth Engine, applying the MNDWI (Xu, 2006) with band 6, threshold -0.2, following methods described in Jones *et al.* (2017). The dry season potential evapotranspiration from each reservoir was subtracted from the dry season reservoir water loss estimates to account for regional differences in potential evapotranspiration rates. Dry season potential evapotranspiration was calculated by multiplying the mean dry season reservoir area by the mean potential evapotranspiration for dry season months over the reservoir. Potential evapotranspiration was derived from mean monthly 1 km x 1km gridded estimates generated from WaterWorld V2.

4.3.2. Analysis

4.3.2.1. Exploring covariates

Principal components analysis

Principal components analysis (PCA) was used to explore which factors explain

most of the variance in the reservoir irrigation presence-absence dataset, for reservoirs with volumes < 10 million m^3, i.e. small and medium sized reservoirs. PCA constructs orthogonal linear combinations of all factors in order to successively explain the variation in the dataset. PCA analysis for this paper was conducted in R using the 'prcomp' function in the 'stats' package (R Core Team, 2018). Before applying PCA, correlations between socio-economic and environmental variables were used to check for redundancy in the dataset (see Appendix E). Labour availability and literacy rate were strongly correlated (R=0.82), however both variables were retained since these were considered conceptually independent. Variables were transformed to a parametric distribution by removing outliers[5] and taking natural logarithms or cubic roots as appropriate[6]. Two variables, 'Deposition rates' and 'Transportation rates' were discarded because they could not be shifted into a parametric distribution and contained 75% of zero values and 91% of <0.01 values respectively[7]. The final dataset contained information for 14 variables across 1116 reservoirs. All variables were standardized by subtracting the mean and converting to Z scores. This process ensures variables are on a comparable scale and removes the effect of range size on PCA outputs (a variable on a scale of 0 to 100 will dominate if others are on a scale of 0 to 1), important since PCA exploits the variance in a dataset.

Statistical significance tests

An analysis of variance (ANOVA) test was used to check whether there were significant differences between the means of each normalized socio-economic variables at reservoirs with 'irrigation and canals', 'irrigation and no canals', and 'no irrigation'. ANOVA

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[5] Specifically, 12 outliers were removed where runoff values were <1m^3.
[6] The skewness and kurtosis of the distributions on each variable were compared under no transformation, transformation using logarithms, and transformation using cubic means. For each variable, the result with skewness closest to 0 and kurtosis closest to 3 was used.
[7] The prevalence of zero or near zero values reflects the gentle slopes in many parts of the Volta basin. While there will still be erosion in such terrain, this will not always be detected by the WaterWorld model which was applied at 1km x 1km resolution for this study and therefore whole reservoir catchments can be perceived as flat with low erosion.

generates an F statistic, which is the ratio of the variation among sample means (responses across irrigation groups) to the variation within groups (responses within the same irrigation group), and a p-value showing the probability that the F statistic for groups with equal means is at least as large as the observed result. A low p-value indicates the means are unlikely to be equal. Where $p<0.05$, Tukey's Honestly Significant Difference (Tukey) post-hoc test was used to determine which groups were significantly different. Tukey generates a p-value showing the probability that the differences between group means divided by the standard error are larger than the expected value in a t-distribution, i.e. means are significantly different. I made boxplots of each significant result to enable visual investigation of the differences in variable distributions between reservoir groups.

For reservoirs with irrigation, an independent two sample T-test was applied to the normalised dataset to check for significant variation in socio-economic factors at reservoirs that were irrigated 'downstream only' and those irrigated 'upstream' (only, or in addition to, downstream irrigation). The T-test generates a T statistic showing the difference between the group means divided by the sum of their mean standard errors, and an associated p-value showing the probability that the group means are different.

All statistical tests were conducted using the R 'stats' package (R Core Team, 2018).

4.3.2.2. Overlay analysis

An overlay analysis was used to identify locations of co-occurrence of factors associated with irrigation uptake. For this, only factors for which a statistically significant difference was identified between irrigated and non-irrigated reservoirs were included, and of those, only factors where data were available for the entire Volta basin, i.e. not only at locations with reservoirs. For example, data on canal presence-absence, reservoir volumes, perimeter-area ratios, and percentage of dry months were not included because they are only available at known reservoir locations. The mean +/- SD of each factor at irrigated

reservoirs were used to define ranges within which irrigation is more likely to occur. Areas falling into this range were given a score of ‘1’ and the multiple factors were overlaid in a GIS to provide a count of the number of factors conducive to irrigation that were present in each location.

4.3.2.3. Assessing sustainability performance

Reservoirs with relatively high (above 75th percentile) food production to water use ratios were compared against those with relatively low (below 25th percentile) ratios, as indicators of good and poor sustainability performance respectively. Socio-economic and environmental characteristics of reservoirs with good and poor sustainability performance were explored using PCA.

4.4. Results

4.4.1. Socio-economic and environmental drivers of irrigation

Principal components 1 and 2 were able to explain 40.2% of the variance in the dataset of reservoir characteristics (Figure 18), with the first three components accounting for 53.6%. Scree plots, correlation matrix statistics and eigenvectors from the PCA are provided in Appendix E. The PCA showed that there is overlap in the characteristics of reservoirs with no irrigation and those with irrigation, yet that reservoirs that have canals and are irrigated are more clearly separated from those with no irrigation. This is to be expected since canals facilitate access to reservoir water and thus without them irrigation is more difficult.

The first principal component explains 21.0% of the variance and is strongly correlated with reservoir volume, perimeter-volume ratio, percentage of dry months, loosely separating irrigation groups based on reservoir **water availability**. The second principal component explaining 19.2% of the variance is dominated by labour availability, literacy rate, infant mortality, population density and access to cities. It can be interpreted as loosely

separating reservoirs based on **poverty levels, market access** and **availability of human resources**.

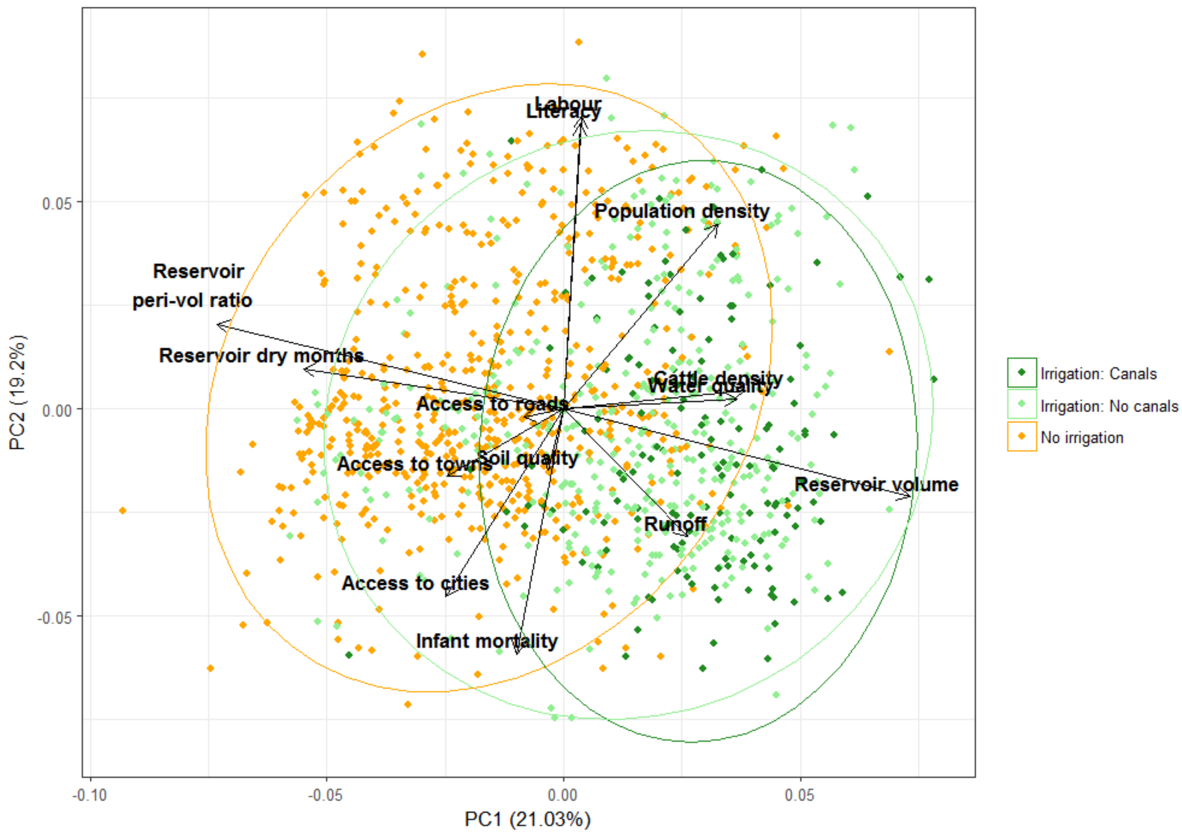


Figure 18: Components 1 and 2 of the principal components analysis of 14 socio-economic and environmental factors associated with reservoirs <10 Mm^3, for which complete data were available (n=1116).

T-tests confirmed differences were significant between **reservoirs with and without irrigation** for all factors related to reservoir water availability (Table 13). Specifically, irrigation is significantly more likely ($p<0.01$) at reservoirs with larger reservoir volumes and higher annual runoff rates, lower perimeter-volume ratios, and fewer dry months. Differences were also significant for labour availability and literacy rates ($p <0.01$), with irrigation more common at reservoirs with lower labour availability and lower literacy rates. These differences are somewhat surprising; I expected irrigation to be more common in areas of higher labour availability where there are lower constraints to finding farm labourers, and in areas where farmers are better educated and have easier access to the

knowledge needed to start irrigating and make irrigation profitable.

There were also significant differences between reservoirs with and without irrigation for factors related to local market access and pressure on water resources. Irrigation is more likely at reservoirs closer to towns with >10,000 inhabitants ($p<0.05$), in locations with higher cattle density ($p<0.01$), areas with higher population density ($p<0.01$), and at reservoirs with lower water quality ($p<0.01$). In contrast, differences were not significant for access to cities or access to roads, factors which are likely to be better proxies for access to large or cross-country markets (while access to towns reflects access to local markets), since the cities dataset is based on settlements with >50,000 inhabitants and the roads dataset considers only primary and secondary roads not minor, earth-covered roads common to rural areas. This therefore suggests irrigation around small and medium sized reservoirs is probably not associated with regional food trade and rather with local food markets.

*Table 13: Statistical differences in means of normalised socio-economic factors between reservoirs <10 Mm3 (n=1116) that have (S1) 'Irrigation' and 'No irrigation', tested using an independent two sample T-test. Significance to the 95% level is indicated by ** and to 99% by ***.*

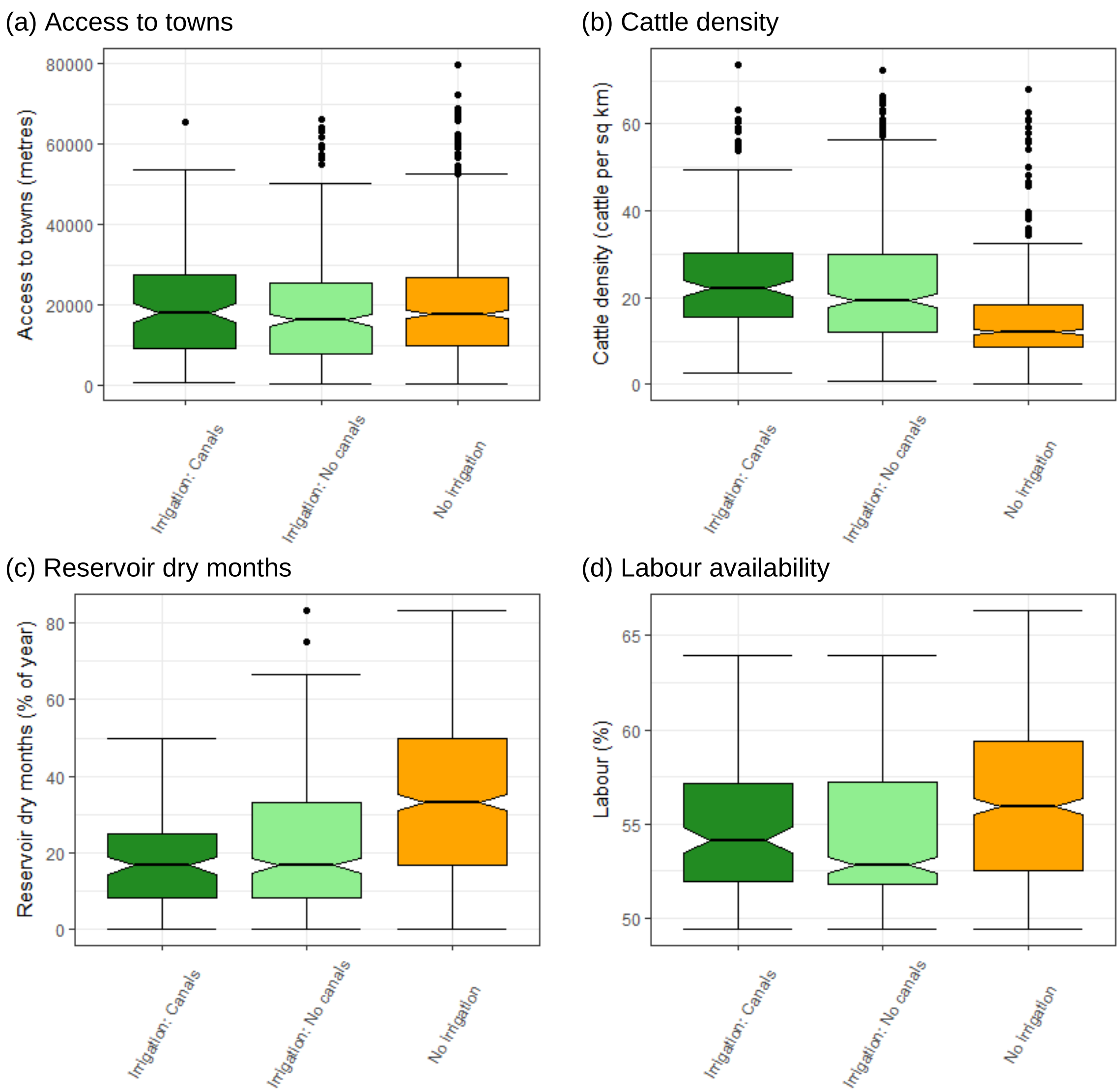
Groups	**Variable**	**Mean +/- SD (irrigation group)**	**Mean +/- SD (no irrigation group)**	**T statistic**	**P-values (two-sided)**
Irrigation - No irrigation	Access to cities (minutes)	51.3 +/- 36.8	53.4 +/-39.6	-0.31	0.755
	Access to roads (metres)	2459.4 +/- 2738.2	2621.2 +/- 2706.7	-1.48	0.140
	Access to towns (metres)	18714.4 +/-13306.2	20422.3 +/- 14392.9	-2.29	0.022**
	Cattle density (cattle per km^2)	24.2 +/- 15.6	14.3 +/-10.3	13	<0.001***
	Infant mortality (%)	12.5 +/-3	12.3 +/-3.2	1.23	0.220
	Labour (%)	54.9 +/-3.9	56.1 +/-4.2	-4.99	<0.001***
	Literacy (%)	36.1 +/- 18.3	39.5 +/-19.1	-2.98	0.003***
	Population density (persons per km^2)	105.4 +/- 60	92.5 +/-66.5	5.43	<0.001***

Groups	Variable	Mean +/- SD (irrigation group)	Mean +/- SD (no irrigation group)	T statistic	P-values (two-sided)
	Reservoir dry months (% of year)	21 +/-18.2	35.1 +/-21.6	-11.79	<0.001***
	Reservoir peri-vol ratio (m per m^3)	0.09 +/- 0.20	0.31 +/- 0.32	-23.52	<0.001***
	Reservoir volume (m^3)	598,439 +/- 1,257,311	35,544 +/- 155,030	23.7	<0.001***
	Runoff (m^3)	18,026,928 +/- 53,643,839	13,259,940 +/- 111,513,423	6.44	<0.001***
	Soil quality (% SOC)	0.7 +/-0.3	0.7 +/-0.3	0.71	0.477
	Water quality (% contaminated)	11.6 +/-8	8.9 +/-6.1	6.55	<0.001***

ANOVA tests for differences between **reservoirs with irrigation and canals, irrigation and no canals, and no irrigation** identified the same ten factors as significant as those identified in Table 13. Figure 19 boxplots of variables where differences were significant between the three groups. A post hoc Tukey test showed that for the ten factors, differences were significant between reservoirs with no irrigation and those with irrigation (*i.e.* with or without canals) for all variables except 'Access to towns' (see Appendix F for full details). Mean distance to a town was 2.0 km greater for 'No irrigation' compared to 'Irrigation: No canals' ($p<0.05$). This result suggests that at reservoirs without canals, irrigation is more likely closer to towns. The easier access to local markets may make irrigation profitable despite the extra effort required to access water.

Differences were also significant between reservoirs with irrigation and canals, and those with irrigation and no canals, for three variables related to the availability of water: percentage of reservoir dry months, reservoir perimeter-volume ratio and reservoir volume ($p<0.01$). These results show canals are more likely to be present at reservoirs where the percentage of reservoir dry months is marginally lower (mean 15.1% compared to 23.4%), perimeter-volume ratios are lower (mean of 0.02 m per m^3 compared to 0.11 m per m^3) and

water volumes are higher (mean of 1.078 Mm^3 compared to 0.410 Mm^3), indicating larger reservoirs attract canal investments. The absence of other significant differences suggests that irrigation at reservoirs without canals is more dependent on factors other than reservoir water availability. Where water availability is adequate, irrigation is likely if other – mainly social and economic - factors that are conducive to irrigation are also present.



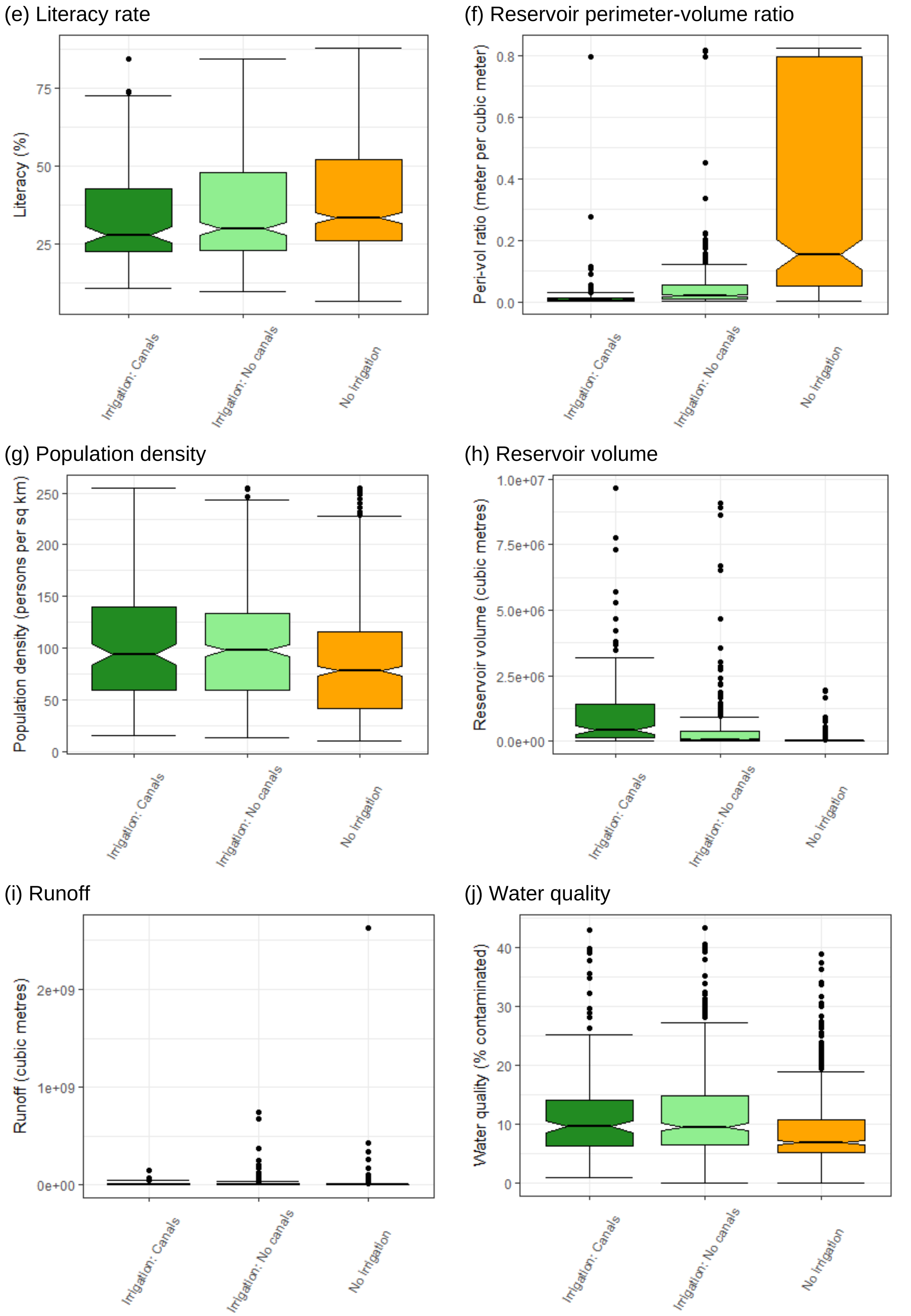

(e) Literacy rate
Literacy (%)
25
50
75
Irrigation: Canals
Irrigation: No canals
No irrigation
(f) Reservoir perimeter-volume ratio
Peri-vol ratio (meter per cubic meter)
0.0
0.2
0.4
0.6
0.8
Irrigation: Canals
Irrigation: No canals
No irrigation
(g) Population density
Population density (persons per sq km)
0
50
100
150
200
250
Irrigation: Canals
Irrigation: No canals
No irrigation
(h) Reservoir volume
Reservoir volume (cubic metres)
0.0e+00
2.5e+06
5.0e+06
7.5e+06
1.0e+07
Irrigation: Canals
Irrigation: No canals
No irrigation
(i) Runoff
Runoff (cubic metres)
0e+00
1e+09
2e+09
Irrigation: Canals
Irrigation: No canals
No irrigation
(j) Water quality
Water quality (% contaminated)
0
10
20
30
40
Irrigation: Canals
Irrigation: No canals
No irrigation

Figure 19: Boxplots for variables where differences between group means were significant. Notches indicate a high likelihood that the median value is different between groups.

The analysis of factors associated with **upstream versus downstream irrigation** highlighted that water availability, access to markets, pressure on resources and human resource availability are influential (Table 14). T-tests showed that at reservoirs used for irrigation, upstream irrigation is significantly more likely, in addition or instead of downstream irrigation, at reservoirs with higher reservoir volumes and annual runoff ($p<0.01$), and a slightly higher percentage of reservoir dry months ($p<0.05$). Regarding reservoir shape, I expected upstream irrigation to be more likely at reservoirs with a larger perimeter-volume ratio, and thus more reservoir edge per unit of water making it possible for a higher number of irrigation plots to be sustained around the reservoir edge. The reason why this is not the case might be that the edge of a reservoir can recede rapidly through the dry season, so even at reservoirs with long perimeters at their maximum extent, upstream cropland will require access to labour or water transport devices to maintain irrigation through the season as the reservoir waterline recedes. Upstream irrigation is more common for larger reservoirs and the distance over which the waterline recedes could be substantial at these reservoirs given the gently sloping terrain in much of the Volta basin, *i.e.* reservoirs are likely to be shallow and extensive in area rather than deep and compact.

Upstream irrigation is significantly more common at reservoirs with better access to towns ($p<0.01$) and therefore local markets, but conversely less common at reservoirs with better access to roads ($p<0.01$) and larger markets. Reservoirs are more likely to be irrigated upstream where there is a relatively high pressure on local resources, including higher cattle and population densities ($p<0.01$), and poorer water and soil quality ($p<0.01$ and $p<0.05$ respectively). Finally, upstream irrigation is more common in contexts with marginally lower literacy rates and labour availability ($p<0.01$).

Table 14: Statistical differences in means of socio-economic factors at reservoirs <10 Mm^3 used for crop irrigation (n=534), where irrigation is 'Downstream only' or only/also 'Upstream', tested using independent T-tests. Significance to the 95% level is indicated by

*** and to 99% by ***.*

Groups	Variable	Mean +/- SD (Downstream group)	Mean +/- SD (Upstream group)	T statistic	P values (two-sided)
Downstream-Upstream	Access to cities (minutes)	52.6 +/-33.9	50.7 +/-38.1	1.04	0.298
	Access to roads (metres)	1894.7 +/- 2249.7	2727.4 +/- 2906.6	-3.15	0.002***
	Access to towns (metres)	21671.5 +/- 12696.7	17310.6 +/- 13375.9	4.22	<0.001***
	Cattle density (cattle per km^2)	20.7 +/-12.3	25.9 +/-16.8	-3.59	<0.001***
	Infant mortality (%)	12.1 +/-3.3	12.7 +/-2.8	-1.87	0.063*
	Labour (%)	55.6 +/-3.5	54.5 +/-4	3.10	0.002***
	Literacy (%)	37.9 +/-13.3	35.2 +/-20.1	3.30	0.001***
	Population density (persons per km^2)	98.5 +/-66.6	108.7 +/-56.3	-3.40	0.001***
	Reservoir dry months (% of year)	18.6 +/-17.2	22.2 +/-18.5	-2.20	0.029**
	Reservoir peri-vol ratio (m per m^3)	0.06 +/- 0.16	0.09 +/- 0.22	1.08	0.280
	Reservoir volume (m^3)	365,679 +/- 777,851	708,934 +/- 1,417,401	-1.54	0.125
	Runoff (m^3)	9,489,682 +/- 22,784,255	22,079,722 +/-62,855,013	-4.35	<0.001***
	Soil quality (% SOC)	0.8 +/-0.2	0.7 +/-0.3	2.37	0.018**
	Water quality (% contaminated)	9.1 +/-5.9	12.8 +/-8.5	-5.59	<0.001***

4.4.2. Spatial co-occurrence of factors associated with irrigation

Figure 20 shows the overlap in socio-economic and environmental factors associated with irrigation uptake, *i.e.* where there were significant differences between reservoirs with irrigation and those with no irrigation (Table 13) and for which there is continuous data coverage across the Volta basin. This includes seven factors: Access to towns, Cattle density, Labour availability, Literacy rate, Population density, Runoff, and Water quality. The overlay analysis indicates that areas along the north-west to south-east diagonal are most favorable for reservoir-irrigation, while the southern, eastern and western

extremes of the basin are contexts with relatively few factors associated with irrigation uptake.

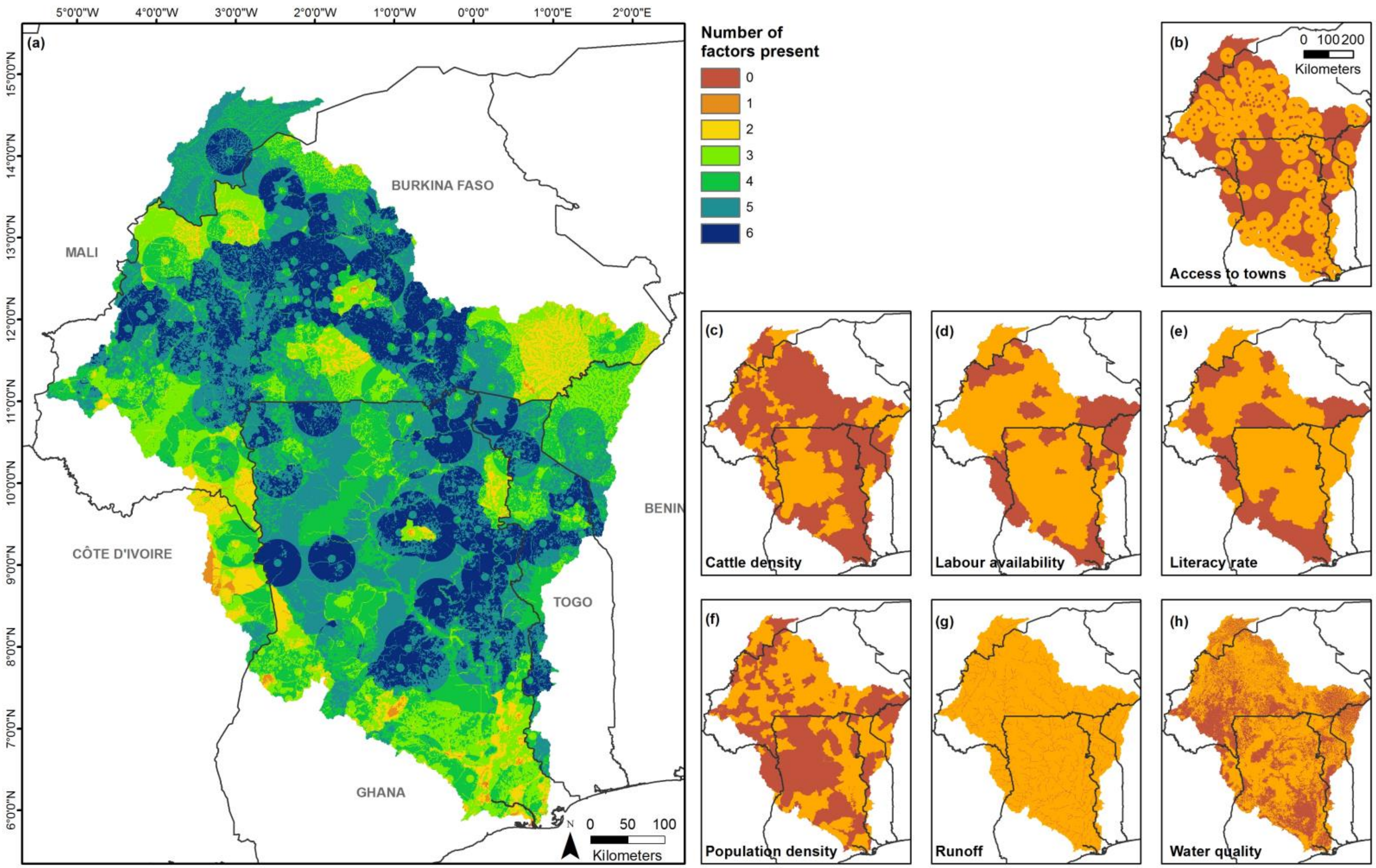


Figure 20: (a) Co-occurrence of factors associated with irrigation uptakea. This map is created by summing maps showing presence or absence of each factor for which there was a significant difference at reservoirs with and without irrigation, for factors with Volta-wide data coverage. Figures (b) to (h) show the presence-absence maps for each factor that was included, created by setting a value of '1' to all areas within the mean+/-SD at irrigated reservoirs, and a value of '0' elsewhere.

4.4.3. Sustainability outcomes

Figure 21 shows the distribution of reservoirs in terms of irrigated area and irrigation water use. Irrigation at reservoirs with high water productivities are more environmentally sustainable, since more food is produced per unit of water. Median water productivity for the 106 (26%) reservoirs with cropland to water use ratios above the 75th–100th percentile ('1-WP100') was 0.36 ha per 1000 m^3. For a crop yield of 10 tons per ha, this is equivalent to 3.6 kg per m^3. For reservoirs in this group, median dry season irrigated cropland area was 3.9 ha. At the other end of the spectrum, 89 (22%) reservoirs in the bottom 25th percentile ('4-WP25') had a high irrigated water use combined with a relatively small irrigated area, and thus deliver poorly in terms of water productivity with an output of 0.01 ha per 1000 m^3.

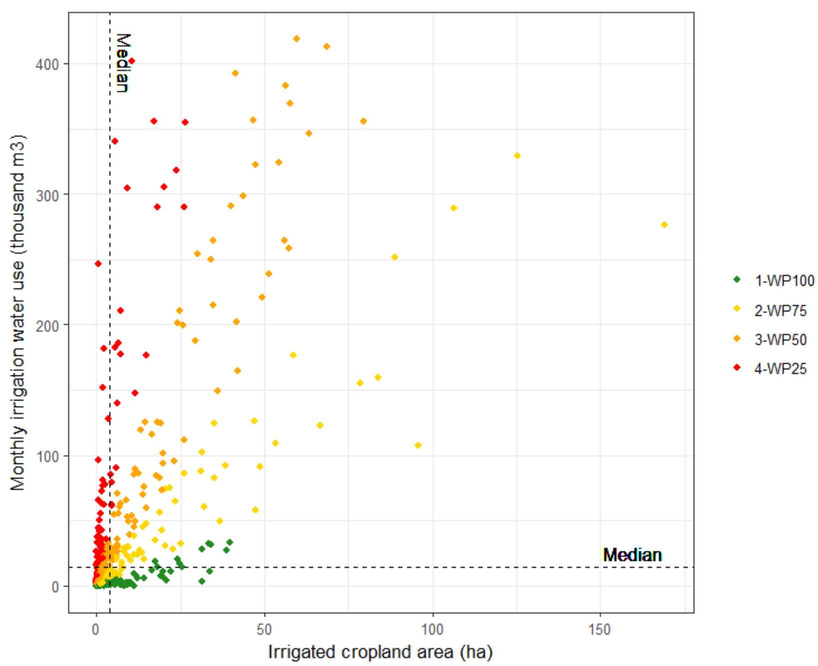


Figure 21: Dry season monthly reservoir irrigation water use against irrigated cropland area at small and medium sized reservoirs used for irrigation and for which water use data could be calculated (n=413; 77% of irrigated reservoirs). Colours represent reservoirs with water productivity in the 75th-100th percentile (1-WP100, green), 50th-75th percentile (2-WP75, yellow), 25th-50th percentile (3-WP50, orange) and the lowest 25th percentile (4-WP25, red).

PCA results show that a primary driver of sustainability outcomes is **reservoir water availability** as determined by reservoir shape and hydrology (Figure 22). Specifically,

reservoirs that are smaller and those that have larger perimeter-volume ratios and more reservoir dry months are likely to have a higher food production to water use ratio. Reservoirs in the 1-WP100 group (highest productivity) have mean volumes of 66,737 m^3 (SD = 90,859), while reservoirs in the 4-WP25 group (lowest productivity) have mean volumes of 753,534 m^3 (SD = 1.167 M). Mean perimeter-volume ratios for these groups are 0.12 m per m^3 (SD = 0.23) and 0.05 m per m^3 (SD = 0.15) respectively, while mean percentage of reservoir dry months are 26% (SD = 16) and 17% (SD = 13).

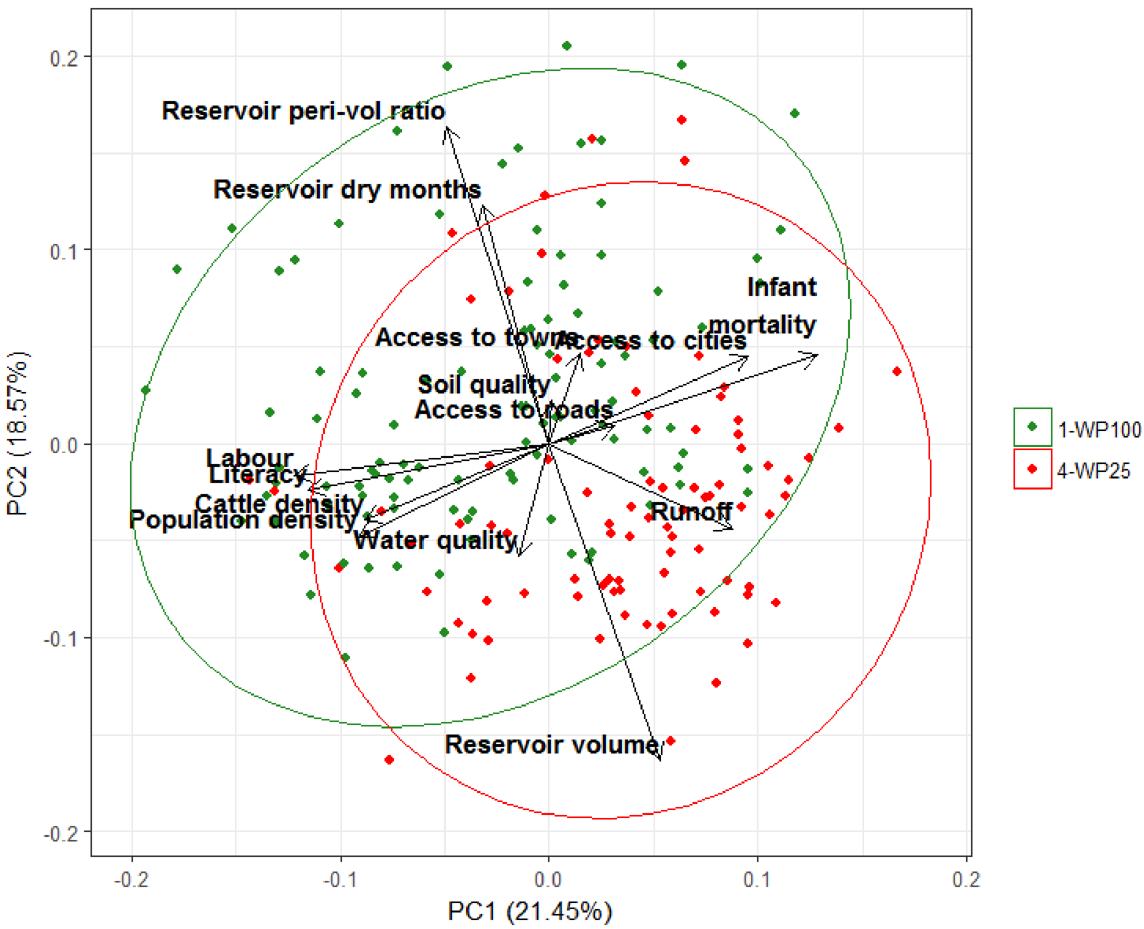


Figure 22: Principal components 1 and 2 of reservoirs with the highest and lowest water productivities, showing variation described in terms of socio-economic and environmental characteristics at each reservoir.

4.5. Discussion

Results show that, for small and medium sized reservoirs in the Volta basin, i)

targeting reservoir placement to locations with several key socio-economic and environmental factors is likely to lead to higher rates of irrigation adoption, ii) irrigation sustainability in terms of irrigated crop production per unit of water could be improved at many reservoirs. I discuss the implications of these results for existing and future reservoir investments aimed at sustainably boosting crop production.

4.5.1. Drivers of irrigation adoption

PCA results show small and medium sized reservoirs in the Volta basin can be loosely characterized based on reservoir water availability, poverty levels, market access and availability of human resources, which explained most of the variance between reservoirs. Results of statistical tests for differences provided more clarity on which factors are most influential. These showed that irrigation uptake is significantly more likely at reservoirs that have better water availability (larger volumes, higher runoff rates, fewer dry months), better local market access (proximity to towns), greater pressure on local water resources (higher population and cattle densities, poorer water quality), and where there are marginally fewer human resources available (slightly lower labour availability and literacy rates).

Most of these results are consistent with localized studies in the Volta basin and our expectations. An exception includes research by Birner et al. (2010) who found that better soil quality was associated with irrigation uptake in the Upper East region, Ghana. This study found no significant difference in soil quality between reservoirs used for irrigation and those that are not, suggesting other factors are more important at the basin-wide level. Another exception is that this study shows that irrigation is more likely in areas with lower education levels while Wekem (2013) found that at two sites in Upper East Ghana, households with better educated farmers were more likely to irrigate. This difference may simply reflect differences in micro (household) versus macro (administrative 2 level) relationships between education level and irrigation adoption. Populations in areas with

lower literacy rates may have a greater reliance on local food production, including irrigation, and reduced capacity to generate alternative sources of income. Yet, education levels in sub-Saharan Africa tend to be lower in rural areas, where education levels lag behind urban environments (Zhang, 2006). Data on education levels used in this paper were strongly correlated with data on labour availability (R=0.82) (see Appendix E). Labour availability was measured here as the ratio of adults to children, which is typically lower in rural areas (Brockerhoff and Yang, 1994). The significant differences in irrigation uptake for reservoirs with different education levels and labour availability may therefore simply reflect an urban-rural divide. Reservoirs in rural areas may be more likely to be used for irrigated cropping than those in urban environments where land is scarce and households have easier access to alternative income sources. This notion is consistent with Birner et al. (2010), who found that irrigation was more likely at isolated dams. However, results of this study showed that irrigation is also more likely at reservoirs closer to towns of >10,000 inhabitants and those situated in more densely populated areas. Further research is therefore needed to confirm the relationship between labour, education and irrigated cropping and possible divisions along urban-rural lines.

This study showed that downstream irrigation – as opposed to irrigation also or only upstream - is more likely at reservoirs with better soil quality. Birner et al. (2010) found that reservoirs with better soil quality generally had stronger reservoir governance systems in place. If this result holds across the Volta basin, the lower prevalence of upstream irrigation at reservoirs with better soil quality in this study may be symptomatic of reservoirs with stronger local management structures able to prevent irrigation activities outside of the official irrigation scheme.

Importantly, results of this chapter show that irrigation is only adopted at small or medium size reservoirs where there is sufficient physical water availability, but that even where this is the case irrigation may not happen if other social, economic and technical

factors conducive to irrigation are absent. It is not enough to provide communities with a reliable source of water; other factors are needed to help make this water accessible for irrigation uses, such as adequate market access and sufficient population density. This result supports other research calling for greater consideration of non-technical aspects of dam interventions to ensure they have a positive impact (Acheampong et al., 2014; Venot et al., 2012, 2011).

The spatial overlay of factors identified as influencing irrigation adoption, as identified form the statistical tests, showed that areas along the north-west to south-east diagonal of the Volta basin are most favorable for reservoir-irrigation adoption while the southern, eastern and western extremes of the basin are less favorable. If community-managed reservoirs are constructed in contexts not conducive to irrigation uptake, they may not lead to increased food production and their overall development impact will be marginal or even negative, e.g. increasing exposure to water-borne diseases (Boelee et al., 2012; Kibret et al., 2009). Future investments should take into account both environmental and socio-economic conditions and alter the intervention to ensure multiple factors associated with irrigation uptake are in place. For example, at reservoirs with relatively high levels of water availability but low household income, households may require additional support, such as credit, loans or more secure property rights, in order to start irrigating (Burney et al., 2013).

4.5.2. Data and scale effects

Reservoir construction dates in the Volta basin range from 1900 to 2015, with most constructed post-1960 (Venot et al., 2012). The distribution of population, labour and other socio-economic and environmental factors, including the capacity of the reservoir, are likely to change over time after a reservoir is constructed. Changes may be triggered by, for example, population growth; opportunities for food production that a reservoir opens up, causing in-migration, income generation and associated ripple effects on education levels

and infant mortality, or; by youth rural-urban migration causing a loss of labour and decline in cropping activities. The relationships between socio-economic or environmental factors and irrigation activities are thus influenced by historic legacies and reservoirs whose contexts are in different stages of transition. Some irrigation activities may remain at sites which have lost many of the conditions favourable for irrigation, while at others irrigation may be on the rise because the context is changing. These subtleties will not be detected in a study such as this one that draws on socio-economic and environmental data from a single timestep. This study merely provides a snapshot of covariates of reservoir irrigation use at one point in time.

The selection of variables was constrained by the coverage and quality of data available. Due to a lack of basin-wide data, this study did not consider several factors that may be influential in driving irrigation adoption, notably reservoir management arrangements, local politics of water, land and seed access, and seasonal changes in labour. In addition, while most of the input data were available at the scale of the reservoirs, the study relied on some data aggregated to the department or district level, e.g. literacy rates and infant mortality. This may have obscured variability in some socio-economic or environmental characteristics of reservoirs. Yet the 400,000 km^2 Volta basin covers such an expanse that using coarse data can provide useful insights that may not be detectable in in depth studies. The trade-offs of working at different scales highlights the value of multi-scale assessments of dam impacts to inform decision-making and of moving beyond single dams to populations of dams.

4.5.3. Increasing food production sustainability through irrigation investments

Are people more food secure in the Volta basin where reservoirs are used for irrigation? Part of the challenge with achieving food security is ensuring food supplies meet year-round requirements, while bringing food demand into sustainable limits and reducing

food waste (Keating et al., 2014). Ensuring increases in smallholder production are environmentally and socially sustainable is necessary to achieve sustainable intensification (Baulcombe et al., 2009; Pretty et al., 2011; Smith et al., 2017) and local and global sustainable development goals (Bhaduri et al., 2016; McKenzie and Williams, 2015).

In communities that have reservoirs used for irrigation, closing food production gaps should be easier because year-round cropping and higher yields result in increased overall production. Katic et al. (2014) found the rainy season rice yield production increased more than three-fold, dry season onion production was introduced (one site), and overall economic profits from irrigated production increased substantially after small reservoir construction at four sites in Burkina Faso. Irrigation is associated with production of a higher diversity of crops, particularly vegetables (Hussain and Hanjra, 2004; Namara et al., 2010), which supply a richer diversity of nutrients helping reduce nutrition-related health problems. In rural parts of the Volta basin that are dominated by subsistence farming and low-market interaction, we might expect household nutritional health to be better among irrigating households than non-irrigators, however no research has been conducted to date to test this. For reservoirs with better market access, irrigation opens up opportunities to produce cash crops (Hussain and Hanjra, 2004) and the additional food created by the reservoir may be sold for income, helping meet the food demands of other households. Indeed this is necessary in order to feed rapidly growing populations across the basin; AGRA (2017) estimates that to ensure adequate food production, each smallholder in Africa now needs to produce enough for its own household, one other rural household, and two urban households.

Chapter 3 showed that reservoir irrigated areas are generally small, averaging 5.5 ha for small (<1 Mm^3) and 33.3 ha for medium size (1-10 Mm^3) reservoirs, and therefore irrigation is likely to be below potential at many reservoirs. If we assume each irrigated plot is 0.25 ha (the mean plot size at the four case study sites) and serves one household, then

a total of 22,352 households are practicing dry season irrigation at small and medium sized reservoirs in the Volta basin. Small reservoirs used for irrigation benefit, on average, 22 households. In contrast, the average medium sized reservoir benefits 133 households. A yield of 10 tons per hectare[8] would result in each of these households receiving 2500 kg additional food. While this represents a noticeable boost to household food supply, the number of beneficiary households and increased food production is very small given the investment costs and potential negative social and environmental impacts of dams. Interventions to help farmers improve overall production (kg), yield (kg/ha), water productivity (kg/m^3), nutritional value (kcal and micronutrients) and earnings from irrigation would increase the benefits of small reservoirs to farmers and society. This may include, for example, promotion of locally adapted and nutritious crop varieties, developing crop and site-specific optimal irrigation schedules, providing funding for reservoir maintenance, providing training on product marketing and removing barriers to market access. Investments in irrigation canals could also help close gaps between actual and potential irrigation output at small and medium reservoirs. Irrigation canals facilitate water access and yet have been constructed at only 14% of small and medium sized reservoirs in the Volta basin, making it harder for farmers to maximise the irrigation potential.

The question remains as to how sustainable reservoir irrigated cropland is for closing food production gaps. Irrigation can sustainably lead to increases in food production by increasing the “crop per drop”, that is crop production per unit of available water (Brauman et al., 2013; Daryanto et al., 2017; Deng et al., 2006). This study shows that 26% of the 413 small and medium sized reservoirs analysed had relatively high food production

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[8] Data on dry season reservoir-irrigated cropland yields in the Votla basin are highly variable. Tomato crop yields at Tono and Dorongo dams in Upper East Ghana were measured at 6.8 t/ha and 12 t/ha respectively (Mdemu et al., 2009). At Binaba and Boura the average vegetable yield was 1-4 t/ha (Poussin et al., 2015). Tomato yields of 20 t/ha were found at some small reservoirs in the White Volta basin (Ofosu et al., 2010)

per unit water use ratios, suggesting that there is room for increasing crop water productivity at the other 74% of reservoirs. Strategies include increasing soil moisture retention capacity, for example by applying crop residues as mulch, so that plants can access more water in the soil; improving irrigation water scheduling to meet (and not exceed) plant water deficits, and; selecting crop varieties that produce the same yields with less water (Ali and Talukder, 2008). These and other water saving strategies are likely to become more important in sub-Saharan Africa in the future where increasingly irregular rainfall patterns make supplemental irrigation a requirement on currently rainfed croplands (Burney et al., 2013). Results of this study show there is a strong relationship between more sustainable agricultural water use and reservoir size and geometry,=. Water productivity was highest at reservoirs with mean volumes of 66,737 m^3 and relatively high (mean of 0.12 m per m^3) perimeter-volume ratios, and lowest at those with mean volumes of 753,534 m^3 and mean perimeter-volume ratios of 0.05 m per m^3. Smaller reservoirs may foster more careful irrigation water management because the resource is scarcer. Reservoirs with larger perimeter-volume ratios enable more farmers to crop adjacent to the waterline, transporting irrigation water by bucket or motor-pump. This suggests there are sustainability benefits of promoting smaller over larger community-managed reservoirs in the Volta basin, and prioritising topographies that create elongated rather than circular reservoirs, although for the latter there will be trade-offs with negative environmental impacts of upstream irrigation that need to be mitigated, e.g. agrochemical and sediment inputs into the reservoir.

4.5.4. Priorities for future impact assessments

I assessed irrigation sustainability by computing the ratio of dry season irrigation extent to reservoir dry season irrigation water loss. This gives an indication of one dimension of environmental sustainability, however further work is needed to understand other sustainability dimensions associated with reservoir irrigation activities including social and economic outcomes and broader environmental impacts. For example, reservoirs impact on

water users downstream, e.g. as water flows in rivers are reduced and the water quality is altered by agrochemicals, and can create conflicts between local farmers who are impacted by the reservoir in different ways, e.g. increased income from irrigation versus increased malaria risk. Constructing and maintaining reservoirs is also a significant financial investment that could be invested in other ways. Future research that account for these factors would provide a more thorough assessment of the impact of reservoirs on food production and sustainability outcomes and help answer the question of whether small really is better.

4.5.5. Limitations of this study

I relied on one-way ANOVAs and t-tests to test for associations between irrigation presence-absence, location and/or canal infrastructure (independent variables) and socio-economic and environmental variables (response variables). The limitation with running a series of one-way ANOVAs or t-tests is that the probability of falsely rejecting the null hypothesis (Type I error) increases with each additional test (Warner, 2008). This problem arises when response variables are interrelated. For example, if two variables are correlated and there are significant differences between groups for both variables, we cannot tell if there is genuinely a significant difference for both variables or the difference between groups for one variable arises because it is correlated with the second variable (Huberty and Morris, 1989).

Despite the risk of inflating a Type I error, multiple univariate tests may be more appropriate than multivariate approaches in some cases. This includes when response variables are conceptually unrelated, or for exploratory analysis (Huberty and Morris, 1989). In this study, none of the response variables were strongly correlated with each other, except labour availability and literacy rate which were considered conceptually unrelated (see Appendix E). This suggests the increased risk of Type I errors due to the use of multiple comparisons was low. However, some pairs of variables were clearly conceptually related,

such as population density and distance to towns. Future research exploring combined effects of these conceptually related variables would be valuable and would help minimise the risk of Type I errors. This could be done using tests such as two-way ANOVAs, MANOVAs and other generalised linear models.

4.6. Conclusion

This paper highlights that the success of small and medium reservoirs in increasing food production through crop irrigation is highly context dependent. Complementing local studies on barriers to irrigation adoption, results show that irrigation uptake at these reservoirs in the Volta basin is more likely at reservoirs with better water availability, better local market access, higher pressure on local water resources, and where there are marginally fewer human resources available. If increased crop production is the aim, all of these factors should be carefully considered when investing in small and medium sized reservoirs to make these development investments effective.

Building evidence of which and where agricultural investments are effective at sustainably improving food production provides an evidence base to help decision-makers plan future investments. The environmental sustainability of current dry season reservoir irrigated cropland could be improved at many reservoirs analysed in this study through increasing crop water productivity. This could be achieved by, for example, crop diversification to include crops with lower water requirements, improving soil conservation practices to increase moisture retention, and optimizing irrigation schedules. Additional impact assessments of small and medium sized reservoirs regionally and globally and at finer scales would be valuable to compare results and build a complete picture for investors of the food production, environmental and livelihood benefits and costs of these investments.

5. Insights into the importance of ecosystem services to human well-being in reservoir landscapes

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Author contributions: S.J. conceived the research. S.J. and N.E. designed the research. M.B. and S.J. collected the data. S.J. analyzed the data. All authors helped write the paper.

Dry season irrigation at community-managed reservoirs may be a promising pathway to sustainably increase crop production in the Volta basin for the benefit of smallholder farmers. Chapter 4 considered the conditions that are conducive to reservoir irrigation uptake at small and medium sized reservoirs and the environmental sustainability of associated irrigated cropland. This chapter focuses on farmer perceptions of human well-being outcomes associated with the benefits provided by community-managed reservoirs and nearby land, referred to as ecosystem services and disservices. Reservoirs are an important source of irrigation water for farmers, yet reservoirs and their surrounding landscapes provide other benefits that may be overlooked if development investments focus only on delivery of irrigation water. Through indepth work in four case study sites, this chapter describes and compares farmer views on the sources and importance of local ecosystem services and disservices. Results are used to discuss how these ecosystem services and disservices affect farmer well-being and implications for sustainable reservoir landscape management.

5.1. Abstract

Smallholder famers in West Africa use multiple ecosystem services (ES) in their day-to-day lives. The contribution that these services make to human well-being (HWB), and therefore to development outcomes, is not well understood. We analyse smallholder farmer perceptions of ES, ecosystem disservices (ED), and their HWB importance around community-managed reservoirs in four semi-arid landscapes in West Africa, using participatory mapping, focus groups and face-to-face surveys. Farmers identified what nature-based benefits (ES) and problems (ED) they perceived across each landscape and rated the importance of each service and disservice for their HWB. Our results indicate that ES make an important contribution to HWB in our study sites. More than 80% of farmers rated benefits from plant-based foods, domestic and agricultural water supplies, biofuel, medicinal plants, and fertile soil, and problems associated with human disease vectors, as of high or very high importance for HWB. Multiple ES were identified as contributing to each dimension of HWB, and ED as detracting from health and material well-being. Perceptions of the importance of several ES and ED varied significantly with socio-economic group, highlighting the need for careful consideration of trade-offs between HWB outcomes and stakeholders in ecosystem management decisions to support sustainable development.

5.2. Introduction

Ecosystem structure and processes can provide benefits that support human well-being (HWB) (Boyd and Banzhaf, 2007; Fisher et al., 2009; MEA, 2005), for example through pollination of crops, filtration of water pollutants, and provision of plant-based medicinal resources. Ecosystem components can also impact negatively on HWB (Campagne et al., 2018; von Döhren and Haase, 2015), notably by spreading livestock and human pests and diseases. The aspects of ecosystems that impact positively and negatively on HWB are referred to here as ecosystem services (ES) and ecosystem disservices (ED) respectively. The concepts of ES and ED are now fairly consistently applied across

ecosystem service science, after a series of pivotal papers clarifying conceptual ambiguities (Boyd and Banzhaf, 2007; Fisher et al., 2009; Wallace, 2007). In contrast, HWB has no standard definition and remains a contested concept (Summers et al., 2012). Income was widely used to measure HWB until attention shifted in the 1990s towards non-economic aspects of well-being, particularly important in development contexts (Sen, 1999). There is now general consensus that HWB is multi-dimensional and that some elements of HWB are universal, such as access to food and shelter, while others are subjective and context-dependent, including happiness and anxiety (Díaz et al., 2015; Schwartz, 1994; Stiglitz et al., 2009). Stiglitz et al. (2009) propose that to inform public policy, both universal and subjective measures of HWB should be considered.

At present, the value of ES for different dimensions of HWB is poorly understood (Olander et al., 2017) and insufficiently captured in wider efforts to improve well-being (Summers et al., 2012). Identifying locally important linkages between ecosystems and HWB has the potential to highlight trade-offs that may exist between potential beneficiaries (Howe et al., 2014) which can facilitate design of ecosystem-based approaches to boost HWB. The Millennium Ecosystem Assessment (MEA, 2005) mapped potential linkages between different ES and dimensions of HWB providing a framework of study. The MEA (2005) views HWB as incorporating freedom of choice and action which stems from sufficient access to material, security, health and social benefits. The Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) provide a newer conceptual framework for nature-people relations, in which HWB is described as achieving a "good quality of life" and embraces the broad definition of HWB suggested by the MEA (Díaz et al., 2015). However, perceptions of the linkages between ecosystems and HWB and their value can vary between individuals and contexts (Boyd and Banzhaf, 2007), depending on factors such as levels of knowledge and what benefits people value or need (Daw et al., 2016). Ecosystems may only provide HWB benefits to specific groups or at certain times or

places (Andersson et al., 2015). For example, the health benefits of medicinal plants may only be important to people who are unwell; income benefits of lowland flooding only important during the cropping season, and; nutrition benefits of wild foods only important in times of household food shortages. Similarly, negative impacts of ecosystems on HWB will vary across stakeholders and space. For example, livestock pests prevalent in lowland areas may be a direct problem only for pastoralists, and malaria vectors to the health of those living near open water.

Identification and disaggregation of the supply and perceived value of ES and ED is important in poverty contexts where community or national level findings can mask household or individual level impacts of ecosystems on a person's well-being (Daw et al., 2011). The way in which people perceive and value ecosystem contributions to HWB influences how these ecosystems are managed (Asah et al., 2014; Hicks et al., 2015; Manfredo et al., 2017). Diverse values amongst stakeholders can impede collective action to manage ES, or result in disjointed actions that have unexpected and sometimes conflicting outcomes (Adger et al., 2009). Here, values refer to "the personal or societal judgement of what is valuable and important in life" (Adger *et al.*, 2009, p338). While economic measures of ecosystem benefits dominate valuation studies (Costanza et al., 2014, 1997; de Groot et al., 2012; Hein et al., 2006), these are critiqued for failing to adequately capture biophysical, social or place-based values (Brown, 2013; Carpenter et al., 2009; Cowling et al., 2008; Folkersen, 2018; Kumar and Kumar, 2008; Sherrouse et al., 2011). Moreover, assigning cash values to nature-based sources of well-being is challenging for some services (Barbier et al., 2011), inappropriate in societies with low levels of market interaction (Christie et al., 2012; Folkersen, 2018), and highly sensitive to methodological factors (Schild et al., 2018), pointing to the need for alternative approaches.

Determining the importance individuals assign to an ES is a social valuation approach (Bryan *et al.*, 2010). Assigned values reflect people's perceptions, worldviews,

preferences and valuation contexts, and can be shared or vary between individuals (Kenter et al., 2015). While many studies have applied non-monetary approaches to ES valuation, relatively little attention has been given to understanding or quantifying local perceptions of the importance of ES (or ED) for HWB in poverty contexts (Daw et al., 2016) and particularly from the perspective of farmers (Smith and Sullivan, 2014); despite their role as primary stewards of a large share of the world's terrestrial land. Theory suggests that farmers should place a high value on ES because their livelihoods depend on adequate freshwater supplies, soil nutrient cycling, biological pest control and other services that support food, fibre and biofuel production (DeClerck et al., 2017; Swinton et al., 2007; Zhang et al., 2007). Yet farmers, including in rural Africa, are increasingly encouraged to turn to technological and agrochemical solutions to farming challenges which may be eroding their sense of reliance on nature with consequences for farmer perceptions, values and behavior regarding ES.

Landscapes containing community-managed reservoirs in the semi-arid northern Volta basin present an interesting focal point for better understanding farmer perceptions and values regarding ES/ED. Created by damming minor rivers, these reservoirs store runoff and create an environment suitable for year-round fish, crop and livestock production. Without a reservoir, agricultural water supplies are limited to the 4-6 month rainy season for most farmers. The reservoirs are also a source of ED, increasing the prevalence of malarial mosquitoes and water-borne diseases such as Schistosomiasis (Boelee et al., 2009; Kibret et al., 2009; McCartney, 2009). Some farmers may give priority to maintaining reservoir water supplies and associated ES at the expense of managing local land to conserve other ES, and despite the increase in ED. Yet due to individual farmer preferences, access rights and livelihood strategies, ES and ED that are mediated by the reservoir may not hold the same level of importance for the HWB of all farmers. Vast sums of money are invested in the construction, expansion and maintenance of community managed reservoirs to support agricultural production in the region (Venot et al., 2012) yet the ES and ED implications of

these reservoirs for local farmers are currently under-researched.

Drawing on methods applied in previous studies to map ES at the community level (e.g. Sinare et al., 2016), eliciting social values for these ES (e.g. Bryan et al., 2010), and comparing values across socio-economic groups (e.g. Iniesta-Arandia et al., 2014; Martín-López et al., 2012), this paper explores farmer perceptions of ES, ED and their importance for HWB in four community-managed reservoir landscapes of West Africa. We focus on **three research questions**:

1. What are local smallholder farmer perceptions of the ES and ED supplied by different land types (locally meaningful areas of distinct land use and/or land cover) in their landscape?
2. What importance do farmers assign to these ES and ED for HWB, and why?
3. How and why do farmer perceptions of the importance of ES and ED vary with ES / ED type and farmer socio-economic profile?

Answering these questions will help close gaps in knowledge regarding farmer perceptions of ES and ED and the implications of ES and ED provided in reservoir landscapes for HWB outcomes. Understanding farmer perceptions of ES is essential to motivating their participation in sustainable land management (Smith and Sullivan, 2014), while knowledge of how important ES / ED are for different farmer groups in reservoir landscapes can provide insights to donors and policymakers on how to make reservoir investments and landscapes meet the needs of a wider range of farmers.

5.3. Materials and methods

5.3.1. Study sites

We selected four agricultural landscapes in seasonally dry portions of the Volta river basin, each containing a small to medium size (0.2 – 1.8 Mm3) man-made reservoir around which several communities live and farm. Our study sites included Bidiga and

Ladwenda reservoirs in Centre-Est, Burkina Faso, and Binaba and Tanga reservoirs in Upper-East, Ghana (

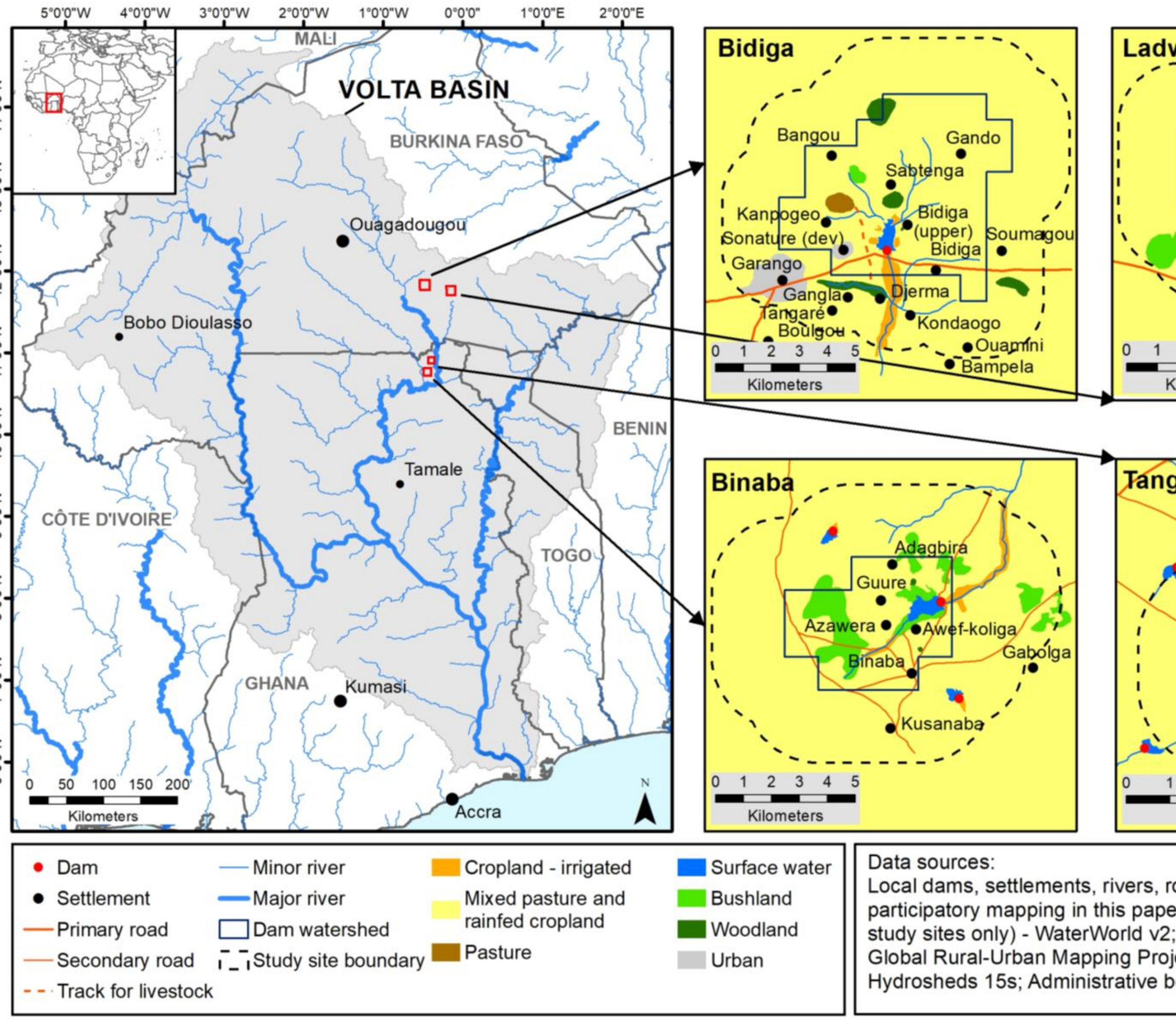


Figure 23). These sites were selected based on evidence of small-scale irrigated cropland around reservoirs, identified from Google Earth, indicating farming activities and to coincide with sites engaged in a Bioversity International led CGIAR Water Land and Ecosystems project in 2015-2016 in order to facilitate stakeholder engagement. We defined the boundary of each site as the area contained by a ~2km buffer around the reservoir, its catchment, and downstream irrigation zone, resulting in sites of 32km2 (Tanga), 57km2 (Binaba), 89km2 (Ladwenda) and 109km2 (Bidiga).

Ghana's Upper-East region, where Binaba and Tanga sites are located, is one of the poorest in the country with 88% of the population living in the two lowest national wealth quintiles, and 38% of the population having no formal education (Ghana Statistical Service and Ghana Health Service and ICF International, 2015). In contrast, Bidiga and Ladwenda sites in the Centre-Est region of Burkina Faso have a much smaller yet still substantial proportion (29%) of the population in the two lowest national wealth quintiles, while nearly three quarters of the population have no formal education (INSD and ICF International, 2012). While this shows within-country poverty levels are relatively high in the Ghanaian sites, 30% of people are estimated to live in multi-dimensional poverty in Ghana compared to 84% in Burkina Faso showing the stark contrast at a cross-country level (UNDP, 2018). Sites in Ghana are home to the Kusasi people. In Burkina Faso, Bissa people dominate the landscape around Bidiga while at Ladwenda nearly all residents are Mossi, part of the largest ethnic group and prevailing land owners in Burkina Faso. A minority of residents in all four sites are from other ethnic groups, including Dagomba and Bissa in the Ghanaian sites and Fulani, Yarsé and Zaossé in the Burkinabé sites. While sites differ culturally, there are strong similarities in socio-economic and agro-climatic conditions. Households in all sites rely predominantly on subsistence and local market agriculture for their livelihoods. Population densities are low with less than 200 persons per km2. There are between three (Ladwenda) and ten (Bidiga) small villages within each landscape, comprising clusters of homesteads. Cropped areas are dominated by rainfed cereals (mainly maize, sorghum, millet, rice) and groundnuts, and irrigated rice, maize, small-scale fruit and vegetable production. Livestock roam freely across gently sloping terrain dominated by cropland intermixed with grassland and sparse tree and bush cover. Rainfall is 700-1000 mm per year and bimodal, with mean annual temperatures of ~28 °C (WorldClim V2; Fick and Hijmans, 2017). Each reservoir is situated within 20 km of a small market town.

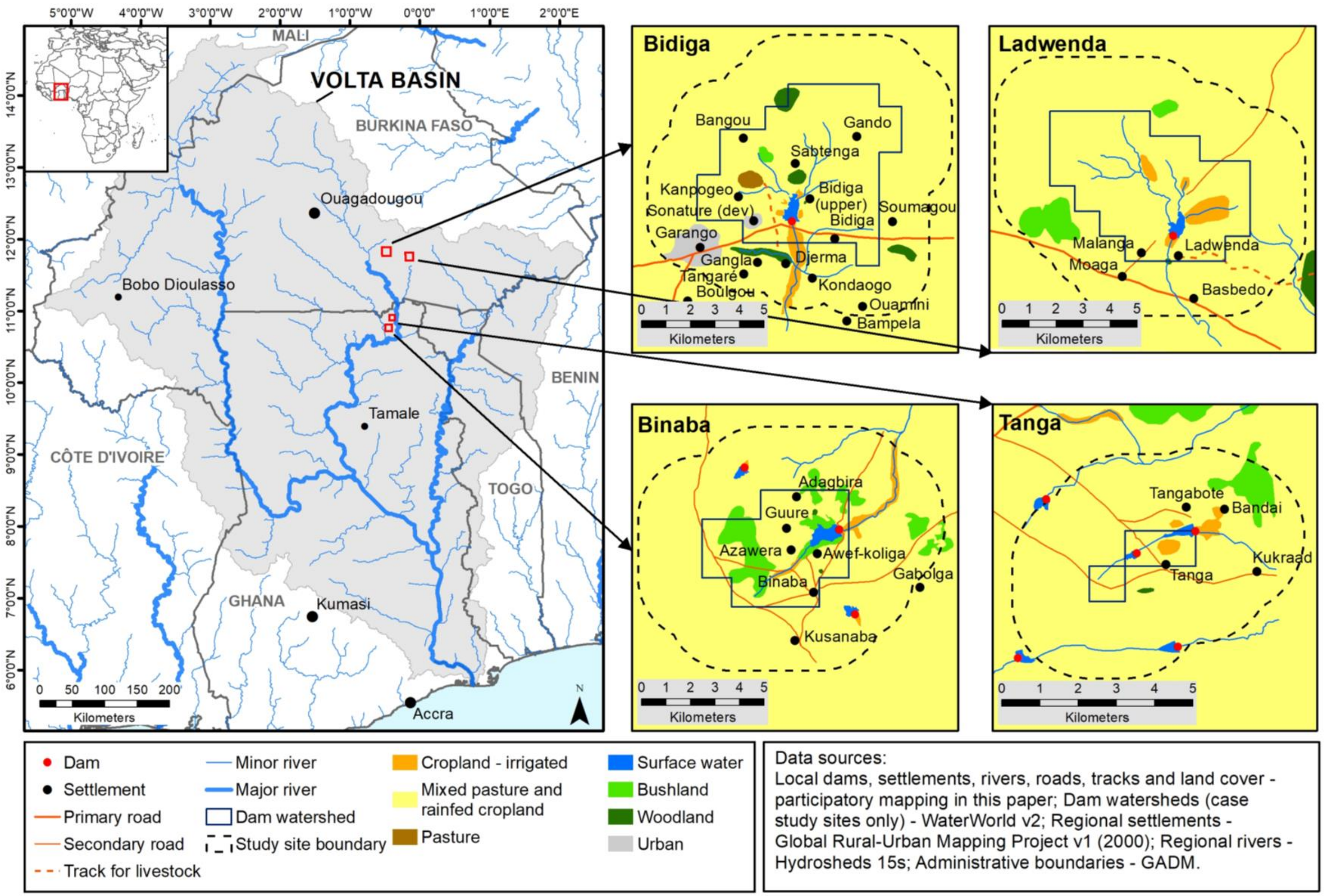


Figure 23: Location of the study sites.

5.3.2. Participant selection

We organised focus groups at each site in December 2016. Dam management associations were asked to invite five men and five women from local farming households targeting a cross section of local villages. At some study sites, fewer than five men or women arrived on the day while in others extra people were invited by the association. In total, 46 representatives from 18 villages across the four communities participated in the ES focus group discussions, comprising 27 men and 19 women. Of these, 37 individuals including at least one representative from each of the 18 villages, were available to participate in a follow-up questionnaire survey, ES/ED rating exercise and semi-structured interview on perceptions of the importance of ES and ED to their wellbeing. Appendix G presents the distributions of participants and villages represented per case study.

5.3.3. Participatory mapping of ecosystem services and disservices

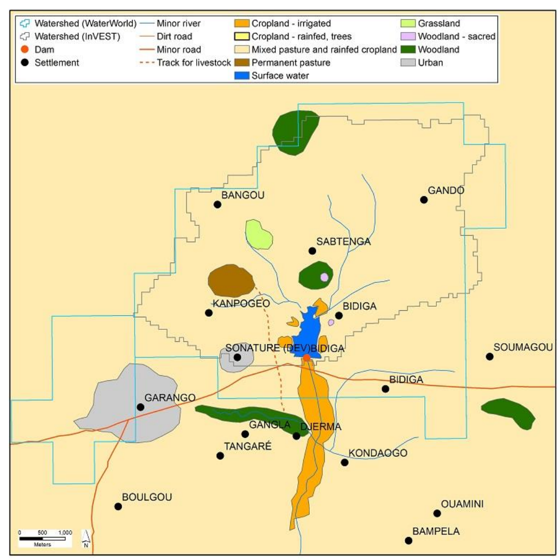
We used a printed 1m x 1m aerial image of each study landscape to identify locations where participants perceive ES and ED. Images were obtained from Google Earth. Using this image, participants were familiarized with visible map features, such as roads, towns and rivers, and asked to describe the different land types present and their boundaries. Participants described the vegetation and use of each land type which we later triangulated using observations we collected during transect walks at each site. The transect walks were conducted with a local villager and involved walking around each reservoir at a distance of about 200m from the reservoir edge, and walking a short way upstream, stopping every 100m for the villager to describe proximate land types and notable features.

Next, participants identified what benefits (ES) and problems (ED) from nature they associated with each land type identified. For this exercise, we used a large matrix of ES and ED cross-tabulated with land types. Many participants were illiterate and therefore the matrix was designed and completed using pictorial symbols as far as possible. We included 14 ES and 2 ED (Table 15) of potential relevance to the communities as determined through

preliminary fieldwork (observation, informal interviews) in April 2016, and invited participants to indicate any additional services or disservices not listed (none were identified). Groups of 5-10 participants disaggregated by gender discussed and then a facilitator marked on the matrix which ES and ED were available in each land type present in their landscape (see Figure 24). Men and women were separated for this exercise to ensure equal participation, which is often a challenge in mixed gender groups (Fortmann, 1995). A facilitator introduced each ES and ED to participants, providing examples from the local context. Once the facilitator was confident participants understood the exercise, participants were disaggregated by gender. Each group had a facilitator and a research assistant to translate to and from the local language (Mooré, Bissa or Kusasi) and English. Due to human error, ED and fodder were excluded in the land type mapping exercise at Binaba and Tanga (but included in all other activities).

(a)

(b)



(c) (d)

Figure 24: Participatory mapping and ecosystem service (ES) and disservice (ED) rating activities. Photos show (a) farmers mapping land types at Binaba, (b) digitized version of land type map produced by participants at Bidiga, (c) a completed matrix of ES and ED (rows) present on each land type (columns) at Bidiga, (d) completed rating from 'No importance' (left) to 'Very high importance' (right) of ES and ED by one participant from Ladwenda.

The groups discussed whether each ES in the matrix is available from a given land type in the Dry Season, Rainy Season or Both Seasons. When consensus was reached, the facilitator marked this information on the matrix.

*Table 15**:** Ecosystem services (ES), disservices(ED) and their classifications used in this paper. We use the Common International Classification of Ecosystem Services to determine ES type and classified an ES or ED as mediated by the reservoir if its supply depends heavily on the presence and functioning of the reservoirs in our study sites.*

Ecosystem service or disservice	**Type**	**Mediated by reservoir**
Food - plant-based	ES-Provisioning	Yes (irrigated crops)
Food - fish		Yes (fisheries)
Food - meat		Yes (livestock watering)
Fodder		No
Water - domestic		Yes (water withdrawals, and reservoir level affects groundwater level)
Water - agricultural		Yes (water withdrawals)
Raw materials (i.e. building materials)		No
Firewood and charcoal		No

Ecosystem service or disservice	Type	Mediated by reservoir
Organic fertiliser		No
Medicinal plants		No
Cultural (places for recreation, traditional or spiritual activities)	ES-Cultural	No
Soil nutrient cycling (fertile soil)	ES-Regulation and maintenance	No
Desirable flooding (for agriculture)		Yes (reservoir capacity and management)
Soil moisture retention (between rains or into dry season)		No
Human disease vectors	ED-Ecosystem disservice	Yes (e.g. habitat for mosquitoes)
Agricultural pests		No

5.3.4. Stakeholder values and socio-economic profiles

A subset of 37 focus group attendees who were available to take part in additional research responded to a short questionnaire on their social and economic status and participated in an ES/ED rating exercise (see Appendix H for a copy of the questionnaire). While rating and ranking are both valid and robust approaches to capturing individual values (Rankin and Grube, 1980), rating can lead to a narrow distribution of scores and results are subject to variations in individual response styles (Alwin and Krosnick, 1985). However, rating items is generally faster and easier for participants, avoids the problem of interdependency between ranked items, and has the key strength is that it does not force participants to artificially differentiate items (Alwin and Krosnick, 1985). For the rating exercise, we asked participants to individually rate the importance of ES for contributing to, or ED for detracting from, their wellbeing, on a 5-point Likert scale from: 1 - No importance, 2 - Low importance, 3 - Moderate importance, 4 - High importance, 5 - Very High importance, using the question “How important is [X ES/ED] for your well-being?”. After two practice runs to ensure understanding, participants were asked to place individual pictorial cards representing each of 14 ES and the 2 ED along the Likert scale, with each participant taking approximately 5 minutes to complete the task. This was followed by a semi-structured interview of around 30 minutes where the participants were asked to explain why they rated

each card as they did.

5.3.5. Explanatory factors behind stakeholder values

5.3.5.1. Statistical analysis

Kruskal-Wallis is suitable for analysing differences in the distribution of an ordinal response variable across more than two groups using the R stats package (R Core Team, 2018). We used Kruskal-Wallis to test for significant differences between the perceived importance of ED and ES across case study sites, and the dunn.test package in R to apply Dunn's test for stochastic dominance and identify which pairs of communities were significantly different.

We similarly used Kruskal-Wallis to test whether the importance assigned to an ES or ED varied significantly with ES or ED characteristics, and whether the importance varied significantly with stakeholder socio-economic profile. Where differences were significant for factors with more than two groups, we used Dunn's test to identify which groups significantly differed. Table 16 describes the data on ES/ED characteristics and participant socio-economic profiles used in the analysis. We selected socio-economic factors that may explain differences in ES/ED perceptions considered in previous research (Iniesta-Arandia et al., 2014; Martín-López et al., 2012) and specific to our case study sites. For example, while age, gender, occupation, education level and income are commonly considered factors, we included ethnicity because of the high ethnic diversity across our study sites, and length of time in the community because reservoirs can attract in-migrants that may have different perceptions of and access to the local landscape compared to autochtones. We included farm area and household dependency ratio as indicators of household wealth in addition to income since many residents in the study sites were thought to have low levels of market interaction. We included life satisfaction and self-assessed health as indicators of respondent well-being, which may affect the importance placed on ecosystems for supporting HWB (e.g. importance ratings may be lower for those who already have high

levels of HWB). We grouped participants into similar class sizes for each factor where possible to help ensure the robustness of statistical tests and checked that each pair of variables were independent or only weakly associated using Chi-squared tests. The strength and significance of associations between socio-economic factors, and contingency tables for associated factors, are provided in Appendix G. We tested the variability in importance ratings across each socio-economic factor for: i) all ES grouped together, ii) all ED grouped together, and iii) individual ES and ED, iv) ES delivery location in relation to the reservoir. Surveys with missing data were excluded from the analyses.

Table 16: Factors used to test hypotheses explaining the variability in importance ratings of ecosystem services (ES) and disservices (ED) across participants.

Hypothesis	**Factors tested** *** indicates tested for ES only, not ED**	**Groups** *** indicates class boundaries defined by median value**	**Group sizes (in class order)**	**Source**
H1: Perceived importance of an ES or ED varies significantly with ES or ED characteristics	ES type*	Provisioning, cultural, regulation and maintenance	10, 1, 3	See Table 15
	ED type	Human disease vectors, Agricultural pests	1,1	
	Delivery location	Reservoir-mediated, not reservoir-mediated	6,8	
H2: Perceived importance of an ES or ED varies significantly with participant socio-economic profile	Age	< 45, ≥ 45 years*	18,19	Individual questionnaire responses
	Length of time in community	< 34, ≥ 34 year*	18,19	
	Gender	Male, female	22,15	
	Ethnicity	Bissa, Mossi, Kusasi, Minorities (Dagomba, Fulani, Yarsé, Zaossé)	10, 8, 13, 6	
	Occupation	Rainfed and irrigated crop farmer, Rainfed crop and livestock or fish farmer, Rainfed crop farmer and/or business activity, where business activities include work as a seamstress, tailor, takeaway food seller, or shopkeeper	16,11,10	
	Household farm area (ha)	< 6, ≥ 6 *	17,20	
	Household income	Very low (<150 Ghanaian cedi or < 25,000 CFA per month) Low (150 to 350 Ghanaian cedi or 25,000 to 50,000 CFA)	13,14,10	

		Moderate (>350 Ghanaian cedi or > 50,000 CFA)		
	Dependency ratio (Number of household dependents ÷ number of household contributors)	< 2.5, ≥ 2.5*	20,17	
	Education level	No education Primary or above (including primary, secondary and other formal education)	22,15	
	Number of times participant too unwell to work in the last year	Never, 1 time, 2 or more times	17,14,6	
	Self-assessed life satisfaction	Satisfied (including Satisfied or Very Satisfied), Not satisfied	25,8	

5.3.5.2. Thematic analysis

We coded and analysed the notes collected during the structured interviews in Nvivo to identify common themes emerging from participant explanations of their reasons for ES/ED importance ratings. We used a grounded theory approach (Denzin and Lincoln, 2000), to avoid forcing responses into predetermined categories.

5.4. Results

5.4.1. Distribution of ecosystem services spatially and seasonally

Focus group participants identified between 7 and 11 land types at each study site. Based on similarities in land use and cover, we reclassified some land types to facilitate cross-site comparisons as shown in Table 17.

Table 17: Land types identified across study sites

Community-identified land type	Identified at which study site				Reclassified land type for cross-site analysis
	Bidiga	Binaba	Ladwenda	Tanga	
Rainfed farmland	X				Mixed pasture and rainfed cropland

Rainfed farmland interchanging with pasture		X	X	X	Mixed pasture and rainfed cropland
Mango plantation interspersed with crops			X		Mixed pasture and rainfed cropland
Irrigated farmland		X		X	Cropland - irrigated
Dry season irrigated farmland	X		X		Cropland - irrigated
Rainy season irrigated farmland	X				Cropland - irrigated
Floodplain farmland			X		Cropland - irrigated
Pasture - temporary	X		X		Mixed pasture and rainfed cropland
Pasture - permanent	X				Permanent pasture
Bush (“Brousse”)		X	X	X	Bushland
Forest			X	X	Woodland
Woodland (“Zone de boisement”	X				Woodland
Surface water	X	X	X	X	Surface water
Hills	X				Bushland
Sacred grove	X	X	X	X	Woodland
Homestead	X	X	X	X	Homestead
Urban market	X	X		X	Urban

Participants disagreed, in a few cases, about the linkages between land type and ES. For example, in Tanga there was no consensus on whether and where soil moisture retention or desirable flooding were present in the landscape.

Gender differences in perceived sources or abundance of ES/ED were not statistically significant. Data from female and male focus groups were therefore combined

to visualize seasonal variability in the availability of ES/ED from each source. The availability of distinct ES and ED from each land type varied across the four case studies, with between 0 and 9 ES identified in any single land type, and between 0 and 2 ED (Figure 25). Participants at two study sites identified the highest diversity of ES to be available from bushland, while at the other two sites the highest diversity was found on mixed pasture and rainfed cropland. This result is somewhat expected since mixed pasture and rainfed cropland is the land type that covers the highest fraction of each landscape followed by bushland. In contrast, coverage of permanent pasture (Bidiga only) or woodland is relatively low, and coverage of other land types is variable. Permanent pasture (one study site), irrigated cropland (two sites) and surface water (one site) were identified as the land types providing the fewest ES.

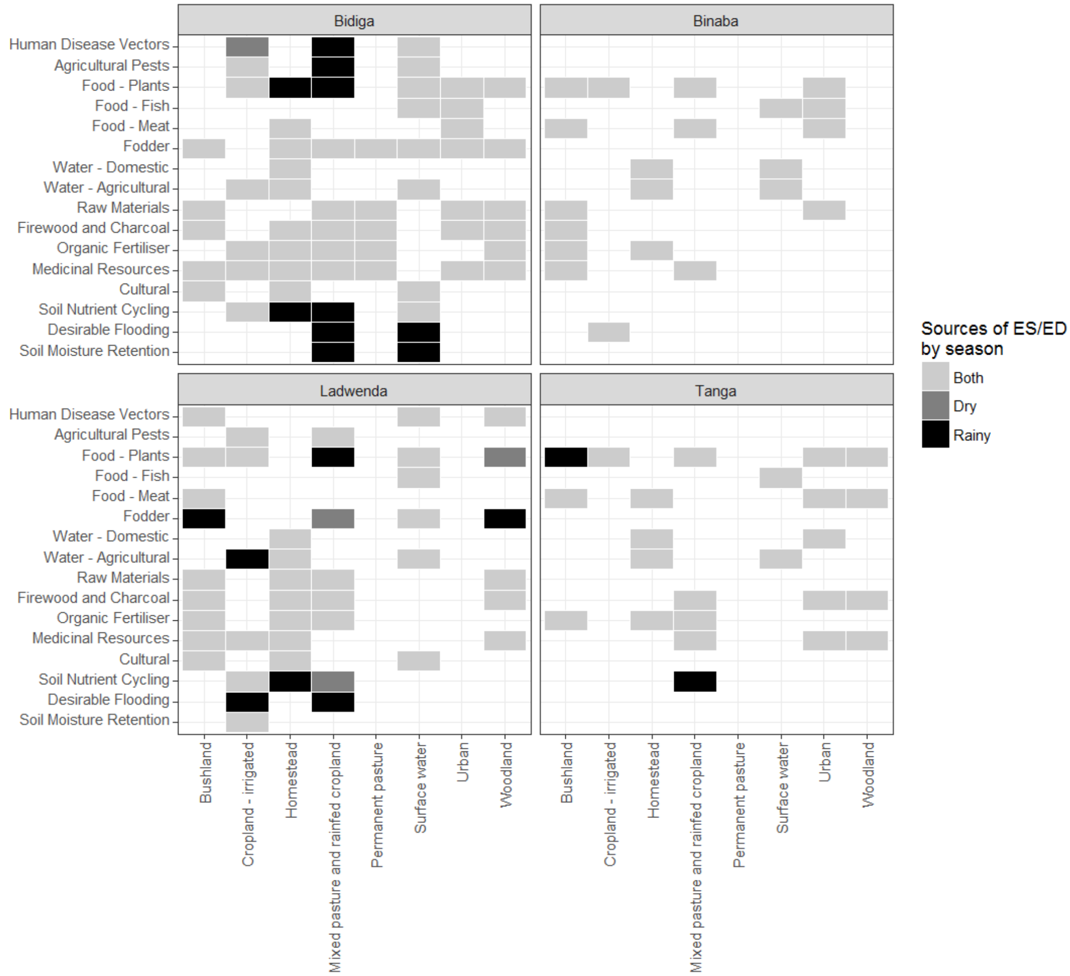


Figure 25: Sources of ecosystem services (ES) and disservices (ED) seasonally, distinguishing ES/ED that are present in "Both" seasons from those present in the "Dry" or "Rainy" seasons.

5.4.2. Importance of ecosystem services and disservices for human wellbeing

5.4.2.1. Participant importance ratings

Participants most commonly rated ES or ED as of high or very high importance to HWB (Table 18). Our data shows that plant foods, medicinal resources, domestic and agricultural water, firewood and charcoal, and soil nutrient cycling were identified as the most beneficial ES, and the human disease vectors the most problematic ED, based on median importance scores. These six ES and one ED were rated of 'high' (4) or 'very high' (5) importance by over 80% of farmers surveyed including for those with "very low" household incomes and/or an "unsatisfied" level of life satisfaction, which we refer to as

underprivileged.

Table 18: Distribution of importance ratings participants assigned to each ecosystem service and disservice and median importance values for all participants and underprivileged groups.

Ecosystem service / disservice	n	% participants selecting each importance level					Median importa -nce	Median importance for underprivileged participants (n=18)*
		Very High (5)	High (4)	Moderate (3)	Low (2)	None (1)		
Desirable Flooding	37	27	22	27	5	19	3	4
Organic Fertiliser	37	43	35	22	0	0	4	4.5
Fodder	37	38	35	24	3	0	4	4
Food – Fish	26	31	31	19	19	0	4	4
Agricultural Pests	37	49	19	11	16	5	4	4.5
Cultural	37	24	30	30	11	5	4	4
Food – Meat	26	19	35	27	8	12	4	3.5
Raw Materials	37	41	24	30	3	3	4	4
Soil Moisture Retention	35	29	26	17	9	20	4	3
Food – Plants	37	86	14	0	0	0	5	5
Medicinal Resources	37	62	22	14	0	3	5	5
Water - Domestic	37	81	14	5	0	0	5	5
Water - Agricultural	37	65	27	8	0	0	5	5
Firewood and Charcoal	37	59	30	5	5	0	5	5
Soil Nutrient Cycling	37	65	24	11	0	0	5	5
Human Disease Vectors	37	73	8	8	5	5	5	5

*Except for Food – Fish and Food Meat (where n=12), and Soil Moisture Retention (where n=17)

5.4.2.2. Dimensions of human well-being and other factors motivating importance ratings

From our coded responses of participant motivations for their ES/ED value judgements, we identified a set of common themes relating to the type of human well-being outcomes, and social, institutional and contextual issues affecting these outcomes. We grouped responses into these themes as shown in Figure 26. Information on who subsequent quote IDs refer to is provided in Appendix I.

In total, 457 (57%) of coded responses related to values participants attributed to

specific HWB outcomes, while the remaining 43% were associated with access to or need for an ES, vulnerability to an ED, or appreciation of nature (Figure 27). At least two ES were associated with each positive HWB outcome and at least one ED or ES with each negative HWB outcome. Negative outcomes from an ES related to, for example, the perception that use of an ES by some people causes problems for others, such as desirable flooding benefiting rice farmers but reducing land available for production of other crops.

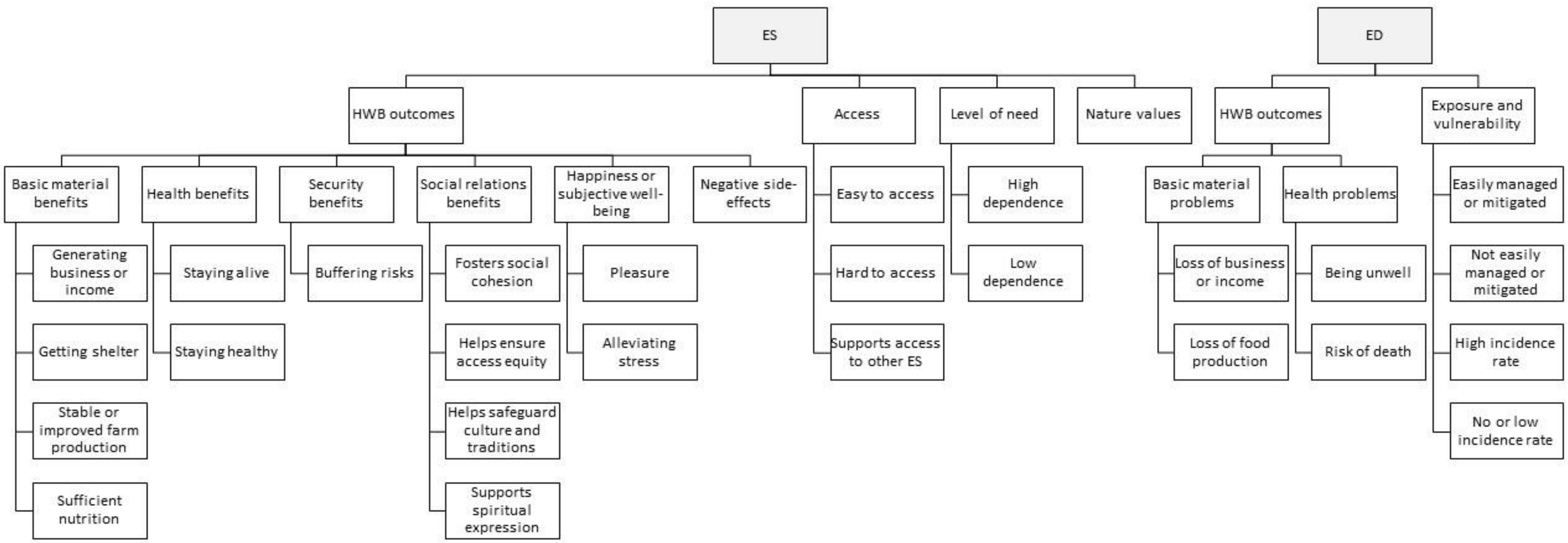


Figure 26: Coding tree showing themes used to group participant reasons for ecosystem service and disservice importance ratings.

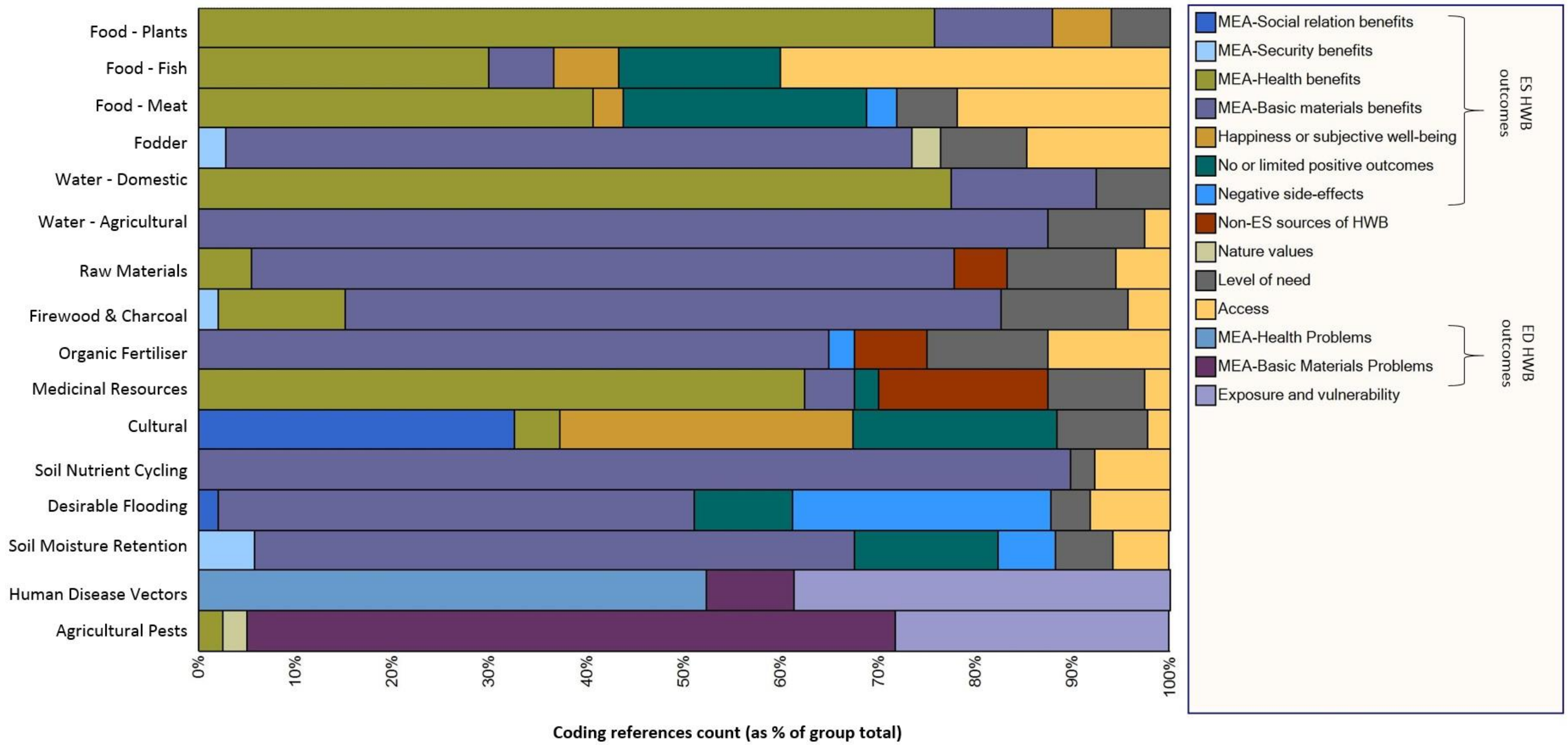


Figure 27: For each ecosystem service (ES) and disservice (ED), percentage of participant reasons for ES and ED importance ratings related to each theme used to code the responses.

Participants most frequently linked **material** and **health** well-being outcomes to ES or ED. Securing stable or improved farm production was the most frequently mentioned material well-being outcome of ES, followed by getting sufficient food, income and finally shelter. Participants valued multiple ES for their contributions to staying healthy, with the latter associated with plant foods, fish foods, domestic water and medicinal resources. Cultural services were associated with maintaining **social relations**, specifically valued for fostering social cohesion, supporting spiritual expression and practices, and helping to safeguard culture and traditions. One Binaba participant who rated cultural services of very high importance explained their inter-generational value: “When children see a place is being conserved for cultural reasons, like a sacred grove, it helps children to be good in the future” (ID: Bin1). Other well-being outcomes motivating importance ratings included **security** benefits, namely the value of fodder and firewood (associated with livestock and wood sales) in surviving times of hardship, and soil moisture retention in helping buffer crop risks during dry spells. Finally, ES contributions to personal happiness or **pleasure** motivated importance ratings for some participants, associated with food (plant, fish and meat-based) and cultural services. Regarding food-related services, pleasure in the taste was given as a reason driving ratings, while happiness, fun and stress-relief were associated with cultural services. For example, a Ladwenda participant shared her view that “Space for football, dancing is important. [It] makes us forget [bad] things that have happened” (ID: Lad8), and a farmer from Tanga who placed a very high importance on cultural services explained: “I feel happy when I am in certain places in nature. When you are worried and you go there, you feel better” (ID: Tan11). This contrasts with some participants who placed a lower priority on cultural services for their HWB; one participant from Binaba explained that “The law says these [places in nature] are important areas, but I don't feel they are that important. If they disappeared it would be ok for me.” (ID: Bin7). The subjectivity highlights the heterogeneity in the ways ES relate to HWB. For ED, health outcomes ranged from being unwell to risk of death associated with human disease vectors (mosquitoes and flies),

while a loss in food production or revenue were mentioned as underpinning HWB importance of agricultural pests. The number of responses relating to HWB outcomes were fairly evenly distributed across the ES and ED, and we used this information to map out which ES and ED farmers associated with different dimensions of HWB (Figure 28).

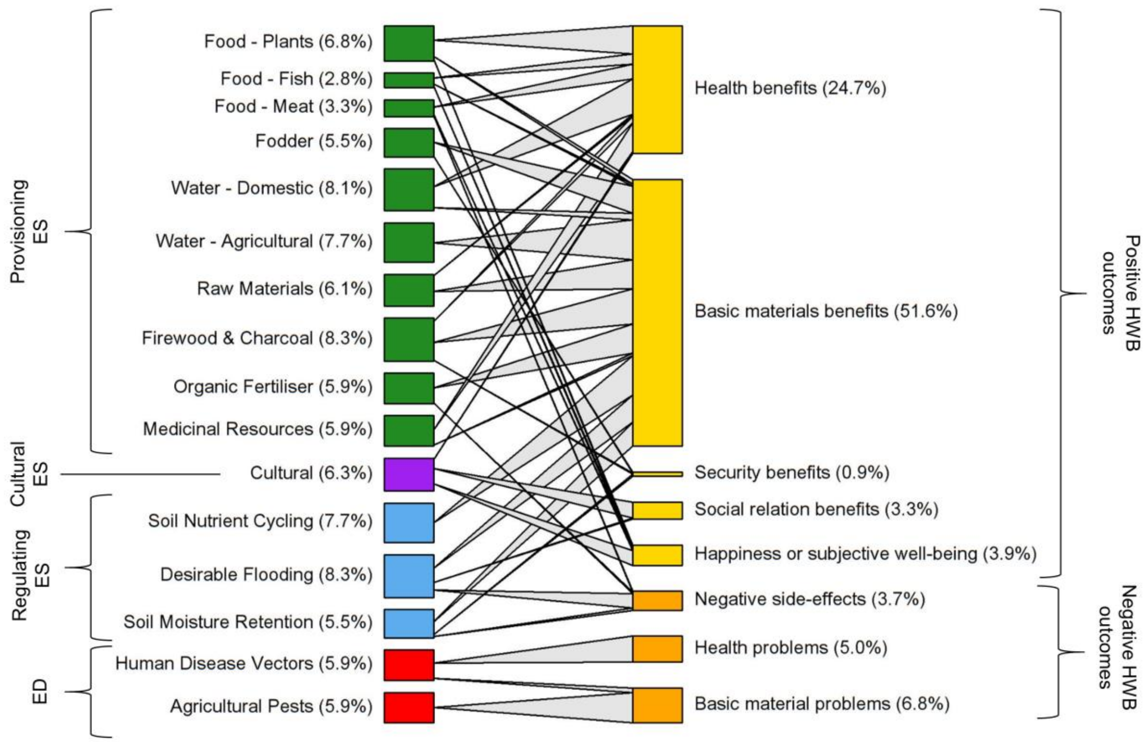


Figure 28: Perceived linkages between ecosystem services / disservices (ES / ED) and human well-being (HWB), based on the n=457 (57%) coded responses which related an ES or ED to specific elements of HWB in participant explanations of their ES / ED importance ratings. The size of the bars reflects the percentage of coded responses related to each ES, ED or HWB outcome, shown in parentheses.

Importance ratings for ES were also found to be influenced by level of need and access. The **level of need** – or dependence on - a service, was mentioned as a factor motivating importance ratings by at least one participant across all ES. A farmer from Tanga who rated meat and fish as of lower importance than plant foods specified, “You can survive without meat or fish. Vegetables are the most important” (ID: Tan7), while a Bidiga farmer explained firewood and charcoal is of moderate importance to him because he uses gas as

well as wood to cook so can cope without wood despite its importance for cooking (ID: Bid4). **Access** to ES, particularly ease of access, was mentioned by several respondents as a factor determining the importance of ES to HWB, particularly for fish and meat foods, fodder, organic fertilizer and desirable flooding (all mentioned by at least five participants). One farmer from Binaba rated fodder as of low importance because it is easy for them to get, "from the countryside, fields or friends" (ID: Bin7), so it is not highly valued irrespective of its contribution to HWB. Similar explanations were given for firewood for some participants from Ladwenda and Binaba. Conversely, difficulty in accessing natural medicinal resources and organic fertiliser underpinned high importance ratings for several participants, while difficulty accessing meat-based foods because of prohibitive costs was mentioned as a reason for both high and low importance ratings (generally lower importance given by those who have access to what they consider suitable substitutes, such as fish and pulses). Another aspect of access is illustrated by the ratings for cultural services. Several respondents stated they had no time to access these services. A farmer from Bidiga, who considered cultural services to have no importance to HWB, explained; "It's young people who spend time outside for fun, not adults" (ID: Bid7).

With respect to ED, a key factor motivating importance ratings, aside from values associated with specific HWB outcomes, included level of **vulnerability** to a decline in HWB associated with the disservice. Several participants who rated ED as of low importance for HWB stated this was because the risks are easily mitigated, for example using mosquito nets to prevent exposure to human disease vectors or pesticides to prevent agricultural pests, or if exposed to the risk they are able to recover quickly, e.g. with medical support or purchasing food. In contrast, several participants who rated ED of high importance for HWB mentioned their lack of capacity to mitigate risks or difficulties recovering. For example, a farmer from Binaba who rated human disease vectors as of very high importance explained his family uses mosquito nets but not every person has one because they are "hard to find

on the market and no longer distributed for free" (ID: Bin7), while two participants from Ladwenda mentioned the high expenditure associated with malaria treatment leading them to consider human disease vectors a problem of very high importance (ID: Lad5, Lad8). Finally, one participant referenced **appreciation of nature** and wanting to ensure not only humans benefit from the land as influencing them to give a lower rating for the importance of agricultural pests, with the participant explaining that it is only fair to let birds eat some of the crop to help sustain their populations even if it causes crop damage (ID: Bid5).

5.4.3. Explanatory factors

5.4.3.1. Importance ratings vary with ES and ED characteristics

For ES, differences in importance ratings between the four case study sites were significant at the 95% level for Soil Moisture Retention (p=0.001), Food - Fish (p=0.011), Cultural (0.023), and Medicinal Resources (p=0.046), and not significant for any other ES. No more than two out of the six possible pairwise site combinations were significantly different for any single ES. For ED, differences were not significant at the 95% level for Agricultural Pests or for Human Disease Vectors. Given importance ratings for the 2 ED, 10 of the 14 ES, and most pairwise combinations of the remaining 4 ES, were not significantly different across communities, we conducted subsequent statistical analyses using combined data.

Participants across our study sites consistently perceived provisioning services as significantly more important than regulating ($p<0.001$) or cultural ($p<0.001$) services, with a median value of *very high* importance assigned to the former, and *high* importance to the latter two groups (see Table 19). Although the median importance of reservoir mediated ES was higher than for ES not mediated by the reservoir, this difference was not statistically significant. In contrast, the perceived importance of ED differed, with Human Disease Vectors considered significantly more important than Agricultural Pests (p=0.049).

*Table 19: Statistical differences in participant importance ratings for ecosystem services (ES) or disservices (ED) grouped by their defining characteristics. Significant results to the 95% level are indicated by *.*

Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
ES type	ES-Cultural - ES-Provisioning	-3.94	<0.001*	4 – 5
	ES-Cultural - ES-Regulation and maintenance	-1.52	0.129	4 – 4
	ES-Provisioning - ES-Regulation and maintenance	3.57	<0.001*	5 - 4
ES relation to reservoir	ES not reservoir mediated – ES reservoir mediated	-1.612	0.107	4 - 5
ED type	Agricultural Pests - Human Disease Vectors	-1.971	0.049*	4 - 5

5.4.3.2. Importance ratings vary with participant socio-economic profiles

Participants from the Kusasi ethnic group assigned a higher importance to all ES combined than those from minority (p=0.007) or Mossi (p=0.025) groups, as did households with lower dependency ratios (p=0.027). Farmers whose livelihoods center on rainfed crop farming and/or business activities tended to rate ES as of higher importance than farmers focused on rainfed cropping and livestock or fishing activities (p=0.005), although median scores were the same (*very high* importance) for both groups. Differences were not significant across other socio-economic groups (Table 20).

*Table 20: Statistical differences in participant importance ratings for all ecosystem services when participants are grouped by socio-economic factors. Significant results to the 95% level are indicated by *.*

Factor	**Groups**	**Z-values**	**P-values (Two-sided)**	**Median Importance (Group 1 – Group 2)**
Age	< 45 yrs - ≥ 45 yrs old	1.305	0.192	5 - 4
Gender	Female - Male	-0.213	0.832	4 - 5
Education	No education – Primary level or above	0.202	0.840	4 - 4
Ethnicity	Kusasi – Minority	2.695	0.007*	5 – 4
	Kusasi - Mossi	2.242	0.025*	5 – 4
	Bissa – Minority	1.838	0.066	5 – 4
	Bissa – Mossi	1.347	0.178	5 – 4
	Bissa - Kusasi	-0.935	0.350	5 – 5
	Minority - Mossi	-0.523	0.601	4 – 4
Household farm area	<6 ha - ≥ 6 ha	-0.627	0.535	4 - 5
Household income	1-Very Low – 2-Low	1.428	0.153	5 – 4
	1-Very Low – 3-Moderate	0.703	0.482	5 – 4
	2-Low – 3-Moderate	-0.616	0.538	4 - 4
Household dependency ratio	<2.5 - ≥ 2.5	2.209	0.027*	5 – 4
Life satisfaction	Not satisfied - Satisfied	-0.239	0.811	5 - 5

Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Occupation	Rainfed crop farmer and/or business activity - Rainfed and irrigated crop farmer	1.597	0.110	5 – 5
	Rainfed crop farmer and/or business activity - Rainfed crop and livestock or fish farmer	2.782	0.005*	5 – 5
	Rainfed and irrigated crop farmer - Rainfed crop and livestock or fish farmer	1.477	0.140	5 – 5
Self-evaluated health (number of times too unwell to work in last year)	1 time – 2 or more times	-1.201	0.230	4 – 5
	1 time – Never	-1.765	0.078	4 – 5
	2 or more times - Never	-0.105	0.916	5 – 5
Time in Community	< 34 yrs - ≥ 34 yrs	-0.914	0.361	4 - 5

Importance assigned to **both ED** considered together varied significantly with ethnicity, with minorities tending to assign a higher importance compared to Bissa or Mossi groups (p=0.039 and p=0.014 respectively). However the median importance was *very high* across minority and Bissa groups, and only marginally lower (between *high and very high*) for the Mossi group. Participants with lower levels of self-assessed life satisfaction perceived ED of significantly higher importance than those that were more satisfied (p=0.030), while the median importance was *very high* for both groups. No other socio-economic factors were associated with statistically significant differences between ED (see Table 21).

*Table 21: Statistical differences in participant importance ratings for ecosystem disservices when participants are grouped by socio-economic factors. Significant results to the 95% level are indicated by *.*

Factor	**Groups**	**Z-values**	**P-values (Two-sided)**	**Median Importance (Group 1 – Group 2)**
Age	< 45 yrs - ≥ 45 yrs old	-1.405	0.160	5 - 5
Education	No education – Primary level or above	0.263	0.792	5 - 5
Ethnicity	Kusasi – Minority	-1.958	0.050	5 - 5
	Kusasi - Mossi	0.807	0.420	5 – 4.5
	Bissa – Minority	-2.061	0.039*	5 – 5
	Bissa – Mossi	0.558	0.577	5 – 4.5
	Bissa - Kusasi	-0.233	0.816	5 – 5
	Minority - Mossi	2.461	0.014*	5 – 4.5
Gender	Female – Male	0.257	0.797	5 - 5
Household farm area	<6 ha - ≥ 6 ha	1.606	0.108	5 - 5
Household income	1-Very Low – 2-Low	-0.713	0.476	5 - 5
	1-Very Low – 3-Moderate	0.040	0.968	5 - 5
	2-Low – 3-Moderate	0.704	0.482	5 - 5
Household dependency ratio	<2.5 - ≥ 2.5	-1.158	0.247	5 - 5
Life satisfaction	Not satisfied - Satisfied	2.177	0.030*	5 – 5
Occupation	Rainfed crop farmer and/or business activity - Rainfed and irrigated crop farmer	1.008	0.313	5 – 5
	Rainfed crop farmer and/or business activity - Rainfed crop and livestock or fish farmer	0.262	0.793	5 – 5
	Rainfed and irrigated crop farmer - Rainfed crop and livestock or fish farmer	-0.746	0.456	5 – 5

Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Self-evaluated health (number of times too unwell to work in last year)	1 time – Never	0.208	0.835	5 – 5
	1 time – 2 or more times	-0.893	0.372	5 – 5
	2 or more times - Never	1.076	0.282	5 – 5
Time in community	< 34 yrs - ≥ 34 yrs	-1.546	0.122	5 - 5

Importance ratings for ES whose delivery is or is not mediated by the reservoir indicate that perceptions differ significantly with ethnicity, occupation and household dependency ratio (Table 22). Bissa and Kusasi people rated ES that are not reservoir mediated as of significantly higher importance than was the case for minority or Mossi ethnic groups ($p<0.05$) while, compared to minority and Mossi groups, Kusasi people rated ES that are reservoir mediated as more important than other ES ($p=0.002$ and $p=0.003$ respectively). This points to potential tensions that may arise if either ES group is prioritized over the other in these landscapes. ES that are reservoir mediated were considered more important to households with lower than average dependency ratios compared to those with higher ratios ($p=0.013$), although within the former group of participants there were also significant differences between ratings for the two ES groups, i.e. some participants with low dependency ratios considered ES that are mediated by the reservoir as significantly less important than other ES ($p=0.033$). Reservoir-mediated ES were considered more important by participants whose occupations centre on rainfed cropping and/or business activities as opposed to rainfed and irrigated cropping ($p=0.011$) or rainfed cropping and livestock or fishing (p.0.019). The same holds true when comparing reservoir-mediated ES against other ES, i.e. farmers in the rainfed cropping and/or business activities group were more likely to rate reservoir-mediated ES higher than non-reservoir mediated ES than were

their counterparts. This difference across livelihood strategies is surprising; we expected to find that farmers involved in irrigated cropping, livestock or fishing activities would place a higher importance on reservoir-mediated ES than other participants, because their livelihoods center around the community reservoir. These results are likely to be a factor of the relatively high importance the RB group placed on Meat Food, which is classified as reservoir mediated, while other reservoir-mediated ES were rated as of similar importance across occupational groups.

Table 22: Statistical differences in participant importance ratings for ecosystem services whose delivery is or is not mediated by the reservoir, when participants are grouped by socio-economic factors. Only significant results to the 95% level are reported.

Factor	**Groups**	**Z-values**	**P-values (Two-sided)**	**Median Importance (Group 1 – Group 2)**
ES not reservoir mediated				
Ethnicity	Bissa - Minority	2.221	0.026	5 – 4
	Bissa - Mossi	2.1	0.036	5 – 4
	Kusasi - Minority	2.139	0.032	4.5 – 4
	Kusasi - Mossi	2.014	0.044	4.5 – 4
ES reservoir mediated				
Household dependency ratio	<2.5 - ≥ 2.5	2.48	0.013	5 - 4
Occupation	Rainfed crop farmer and/or business activity - Rainfed and irrigated crop farmer	2.555	0.011	5 – 4
	Rainfed crop farmer and/or business activity– - Rainfed crop and livestock or fish farmer	2.348	0.019	5 – 5
All ES grouped by reservoir mediation				

Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Ethnicity	Minority & ES not reservoir mediated – Kusasi & ES reservoir mediated	-3.065	0.002	4 – 5
	Mossi & ES not reservoir mediated - Kusasi & ES reservoir mediated	-3.011	0.003	4 – 5
Household dependency ratio	<2.5 & ES not reservoir mediated - <2.5 & ES reservoir mediated	-2.13	0.033	4 – 5
	≥ 2.5 & ES not reservoir mediated - <2.5 & ES reservoir mediated	-2.911	0.004	4 – 5
Occupation	Rainfed crop farmer and/or business activity & ES not reservoir mediated - Rainfed crop farmer and/or business activity & ES reservoir mediated	-2.247	0.025	4 – 5
	Rainfed and irrigated crop farmer & ES not reservoir mediated - Rainfed crop farmer and/or business activity & ES reservoir mediated	-2.431	0.015	5 – 5
	Rainfed crop and livestock or fish farmer & ES not reservoir mediated - Rainfed crop farmer and/or business activity & ES reservoir mediated	-3.783	<0.001	4 – 5

The importance of each individual ES varied significantly between socio-economic groups, with the exception of Firewood and Charcoal, and Organic Material. In particular, ratings for food and water-related ES varied along several socio-economic lines. Individuals who consider themselves healthy – never too unwell to work during the last year – placed a higher importance on Plant Foods than participants with poorer health (p = 0.043). This may

reflect a keener appreciation and utilization of plant based foods for staying healthy in the former group, who expressed the view that plant foods are the basis for healthy diets and bodies (ID: Bid4, Bin2, Lad11, Tan1) whereas several participants with poorer health focus on the livelihood (ID: Bid6, Lad4) and taste benefits (ID: Bin7, Bit5) of plant based foods as motivating their value judgements. Participants from households with lower than average dependency ratios rated Fish and Meat Foods of significantly greater importance than those with higher dependency ratios ($p = 0.006$ for fish, $p = 0.022$ for meat). This may be a result of a greater capacity to access fish and meat among the former group who should have more resources per capita. However, there were no significant differences between Fish and Meat Food ratings across other measures of household wealth, namely household income and farm size, so this result would benefit from further exploration. Interestingly, Bissa and minority ethnic groups rated Fish Foods as less important than their Kusasi counterparts ($p=0.002$ and $p=0.029$ respectively). Analysis of interview responses indicates this may be because of a heightened appreciation of the health benefits of fish among Kusasi people, with several Kusasi participants explaining that fish makes you "strong" (ID: Bin2, Bin8, Tan2), compared to a tendency for other participants including Bissa and minorities to state that fish is "non-essential" to the diet (ID: Bid1, Bid4, Bid7). Meat was considered more important by farmers with rainfed cropping and business-based livelihoods, compared to those focused on rainfed and irrigated cropping ($p=0.033$). The former group valued meat for giving "energy" (ID: Bin2, Bin6, Bid8) and preventing illness (Bin2, Bin3, Bid6), while the latter group expressed the view that meat is non-essential for remaining healthy (ID: Tan1, Tan3, Tan7) and often inaccessible due to prohibitive prices (ID: Bid1, Bid2, Tan5, Lad11). Meat tends to be market purchased rather than sourced from the landscape or homestead in the case study sites, so it is also possible that farmers with business activities may have easier access to markets facilitating inclusion of meat in the diet.

Younger people and those with no education valued Agricultural Water significantly higher than older and better educated people (p = 0.003 and p = 0.023 respectively). Interview responses showed that the former groups consistently mentioned the importance of irrigation water for food consumption at home and particularly during the dry season, and for sustaining livestock through the year, whereas the latter groups, while also valuing agricultural water for its dry season benefits, were more likely to relate this to providing a source of income rather than home food consumption. Desirable Flooding was rated of significantly higher importance by women (p = 0.006) and participants that were relatively new to the community (p = 0.015), as well as individuals who have livelihoods based on rainfed cropping with business activities (p=0.002) or irrigated cropping (p=0.007), rather than those based on livestock or fish farming. The latter result is unsurprising since flooding primarily benefits rice cultivation in the study sites. Meanwhile, at Binaba, one participant (ID: Bin7) explained that floodplains are generally divided among women (not men) for farming and this is why they are so important to women farmers at this site. At other sites, women's perceptions of the production value of flooded areas was generally favorable, highlighting that these areas give a good production particularly for rice (ID: Bid1, Lad10, Lad11, Lad12), whereas men tended to consider these areas as unproductive (ID: Bid4, Bid6, Tan3, Lad6, Tan5). Gender was weakly associated with length of time a participant had spent in the community in our dataset (see Appendix G). Women were more likely to be newer to the community likely due to local tendencies for women to move into their husband's house on marriage. As a result, gender may in part explain the divergence in desirable flooding ratings across groups who have spent different lengths of time in the community. However, the latter result may also reflect the increased importance floodplain farming has for migrants, who tend to have less secure land and water access compared to autochthones. Desirable flooding was also rated higher by participants from households with a very low income compared to moderate earners (p = 0.049), and those with smaller than average farm holdings (p = 0.011). These results may be associated with land access issues

and that natural floodplains are more accessible to these groups, and therefore play a more important role in their livelihoods, than areas within the (paid) irrigation scheme.

For individual ED, farmers who had resided longer in the community (p = 0.010), or reported lower levels of life satisfaction (p = 0.039), considered Agricultural Pests of significantly higher importance for detracting from HWB compared to other participants. This was also the case for minority ethnic groups compared to Bissa or Mossi people (p=0.003 and p=0.010 respectively) and for Kusasi people compared to Bissa (p=0.038). Reasons provided by these groups for giving higher ratings relate primarily to the risk of crop failure due to damage from termites, worms and rodents, while other participants were more likely to consider these problems mitigatable with the use of pesticides. Therefore group differences are likely to reflect different perceptions towards the use of, and levels of access to, pesticides across participants. In addition, farmers whose livelihoods are more affected by agricultural pests may experience lower levels of life satisfaction, helping explain the difference in importance ratings for groups with different life satisfaction levels. The importance of Human Disease Vectors varied slightly with household farm area (p = 0.043), though median values remain *very high* across groups. Table 23 and Table 24 present the full list of which ES and ED significantly differed with which socio-economic factors.

Table 23: Statistical differences in participant importance ratings for single ecosystem services, when participants are grouped by socio-economic factors. Only significant results to the 95% level are reported.

ES	**Factor**	**Groups**	**Z-values**	**P-values (Two-sided)**	**Median Importance (Group 1 – Group 2)**
Food – Plants	Household income	2-Low – 3-Moderate	-1.991	0.046	5 – 5
	Self-evaluated health (number of times too unwell to work in last year)	2 or more times - Never	-2.025	0.043	5 – 5

ES	Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Food – Fish	Ethnicity	Bissa - Kusasi	-3.034	0.002	2.5 – 5
		Kusasi - Minority	2.183	0.029	5 – 3
	Household dependency ratio	<2.5 - ≥ 2.5	2.746	0.006	4 – 3
Food - Meat	Occupation	RB - RI	2.133	0.033	4 – 3
	Household dependency ratio	<2.5 - ≥ 2.5	2.286	0.022	4 – 3
Fodder	Household income	2-Low – 3-Moderate	-2.172	0.030	3 – 4.5
Water - Agricultural	Age	< 45 yrs - ≥ 45 yrs old	2.998	0.003	5 – 4
	Education	No education – Primary level or above	2.280	0.023	5 – 4
Water - Domestic	Occupation	Rainfed crop farmer and/or business activity - Rainfed crop and livestock or fish farmer	2.073	0.038	5 – 5
Raw Materials	Occupation	Rainfed crop farmer and/or business activity - Rainfed crop and livestock or fish farmer	2.078	0.038	5 – 3
Medicinal Resources	Ethnicity	Kusasi - Mossi	3.252	0.001	5 – 3
		Bissa - Mossi	2.570	0.010	5 – 3
	Occupation	Rainfed and irrigated crop farmer - Rainfed	2.081	0.037	5 – 4

ES	Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
		crop and livestock or fish farmer–			
Cultural	Ethnicity	Bissa – Mossi	-2.526	0.012	3 – 4.5
		Bissa – Kusasi	-2.318	0.020	3 – 4
Desirable Flooding	Time in community	< 34 yrs - ≥ 34 yrs	2.439	0.015	4 – 3
	Gender	Female – Male	2.722	0.006	4 – 3
	Occupation	Rainfed crop farmer and/or business activity - Rainfed crop and livestock or fish farmer	3.044	0.002	4 – 2
		Rainfed and irrigated crop farmer - Rainfed crop and livestock or fish farmer–	2.700	0.007	4 – 2
	Household farm area	<6 ha - ≥ 6 ha	2.541	0.011	4 – 3
	Household income	1-Very Low – 3-Moderate	1.961	0.049	4 – 3
Soil Moisture Retention	Ethnicity	Bissa – Mossi	3.279	0.001	4 – 1
		Kusasi – Mossi	3.014	0.003	4 – 1
		Bissa – Minority	2.713	0.007	4 – 2
		Kusasi - Minority	2.422	0.015	4 – 2

Table 24: Statistical differences in participant importance ratings for single ecosystem disservices, when participants are grouped by socio-economic factors. Only significant results to the 95% level are reported.

Factor	Groups	ED	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Agricultural Pests	Time in community	< 34 yrs - ≥ 34 yrs	-2.569	0.010	3.5 – 5
	Ethnicity	Bissa – Minority	-2.949	0.003	3 – 5
		Bissa – Kusasi	-2.074	0.038	3 – 5
		Minority - Mossi	2.563	0.010	5 – 3.5
	Life satisfaction	Not satisfied - Satisfied	2.065	0.039	5 – 4
Human Disease Vectors	Household farm area	<6 ha - ≥ 6 ha	2.028	0.043	5 – 5

5.5. Discussion

This paper focused on understanding farmer perceptions of ES and ED in four West African landscapes containing community-managed reservoirs, and applying a social valuation approach to assess the importance farmers attribute to ES and ED for maintaining HWB. This is the first paper we know of that investigates farmer perceptions of and values regarding ES and ED in community-managed reservoir landscapes. We show that a diversity of ES and ED are perceived as important for local well-being in these landscapes and explore how and why values for some ES and ED diverge along socio-economic lines. The paper explicitly captures smallholder perceptions of the relationships between specific ES, ED and HWB outcomes in the case study landscapes, helping to close a gap in knowledge regarding context-specific ecosystem contributions to different dimensions of HWB. In this section, we place our findings in the context of other research and use the results to discuss potential implications for local reservoir and ecosystem management.

5.5.1. Spatio-temporal distribution of ecosystem services and disservices in reservoir landscapes

In our case study sites, farmers identified a diversity of ES supplied by multiple land types, highlighting the multifunctionality of these rural landscapes. This result is consistent with other regionally proximate ES studies (Malmborg et al., 2018; Sinare et al., 2016). Mixed pasture and rainfed cropland or bushland were perceived to provide on average a higher diversity of ES (between 3 and 7 ES) than any other rural land type. Other studies have similarly found that small-scale farmers perceive a wide variety of ES including from agricultural land (Teixeira et al., 2018). Recognition of ES is likely to depend on many factors including culture and tradition, yet in smallholder farming contexts may also be a result of farmers tending to depend less on external inputs and more on the natural ecosystem functions that help co-produce food (Power, 2010; Swinton et al., 2007; Zhang et al., 2007). Urban areas were identified as sources of provisioning ES in three of the case studies, highlighting that some ES are purchased as well as harvested directly from the land. These ES include plant, fish and meat foods, raw materials, charcoal and medicinal resources. Safeguarding natural sources of these products may be less important at some sites for ensuring ongoing local access than safeguarding cultural and regulating ES or those provisioning ES that are not available through markets, such as fodder, freshwater and organic fertiliser. Loss of natural sources of the latter services would likely be harder for farmers to replace.

Seasonal variability in ES and ED supplies was associated primarily with food and water-related ES and ED. This is likely to be due to seasonal fluctuations in surface water availability and flood regimes; low levels of market-interaction leading to high dependency on local, seasonally variable food production, and; the difficulty storing ES through the dry season, e.g. fresh fruit and vegetables, fodder and domestic water. Actions to improve access to ES should therefore include tackling these temporal gaps in supply, such as through improving local ES storage capacities (e.g. vermin-proof food and fodder stores,

rainwater harvesting, raising soil moisture storage capacity) and limiting seasonal fluctuations in ES market prices (e.g. meat, fish and vegetables).

5.5.2. Ecosystem service and disservice importance for human well-being

In our study, plant foods, medicinal resources, domestic and agricultural water, firewood and charcoal, and soil nutrient cycling were consistently considered the most beneficial ES, and the human disease vectors the most problematic ED for achieving HWB outcomes, based on median importance scores. These six ES and one ED were rated of ‘high’ (4) or ‘very high’ (5) importance by over 80% of farmers surveyed including for those with the lowest household incomes and/or lowest levels of life satisfaction. The HWB outcomes associated with the six most important ES related predominantly to health and basic materials, including having stable or improved farm production, generating income, staying healthy, and getting adequate nutrition (clean water, sufficient food), while human disease vectors were associated with financial stress, poor health and even death. Bushland (at all four case study sites), woodland (three sites), irrigated cropland (two sites), and surface water (one site) were identified as providing two or more of the six most beneficial ES, while also being identified as sources of human disease vectors at one or more site. This points to a direct trade-off between ES and ED that may need to be taken into account when managing land type extent and configuration to secure ecosystem-based HWB outcomes. It also highlights the value of conserving bushland zones in these reservoir landscapes; loss of bushland would pose a risk to the supply of multiple locally important ES that are connected to health and material benefits for local farmers. The biggest risks to bushland in these landscapes are over-harvesting of firewood, over-grazing, and encroachment of agricultural land. These risks could be mitigated by increasing household use of alternative energy sources combined with facilitating controlled grazing and increasing productivity of existing cropland to help limit further cropland expansion.

Our results showed that provisioning services were perceived as significantly more

important than regulating and maintenance or cultural services. This is likely to be because individual perceptions of value tend to be biased towards where there is a simple connection between the ecosystem process and its end-benefit (Costanza et al., 2014). This nonetheless points to a risk that regulating and maintenance or cultural services will be given a lower priority in farmer land management decisions designed to conserve ES, because the benefits they provide are less tangible rather than because the benefits are less important to HWB. ES are often interconnected (Vallet et al., 2018) and loss of a regulating service, such as soil nutrient cycling, may reduce provision or quality of provisioning or other services, such as food production and firewood provision. Indeed, the interconnectedness of ES and water scarcity in semi-arid areas means that maintaining water-related ES must remain a priority to safeguard supplies of other dryland services (Le Maitre et al., 2007). Discussing the interconnectedness of ES with farmers in the case studies may be useful to identify possible (unexpected) trade-offs between ES and HWB outcomes that could arise from changes to reservoir and land management.

Participant explanations for why they assigned ES / ED importance ratings indicate the ES ratings were primarily a function of the perceived value of the HWB outcome to which an ES makes a contribution and/or; how accessible the ES was to the person, and/or how dependent the person was on the ES for the HWB outcome. In contrast, the perceived value of the HWB outcome and participant level of vulnerability to ED influenced how important the ED was for HWB. This suggests that altering levels of access to and need for ES, and vulnerability to ED, may alter the perceived importance of the contribution ES make to HWB, making these entry points for managing ES for more equitable HWB outcomes. The HWB outcomes associated with the six most important ES related predominantly to health and basic materials, including having stable or improved farm production, generating income, staying healthy, and getting adequate nutrition (clean water, sufficient food). These elements of HWB are high on the agenda of globally agreed development priorities

encapsulated in the Sustainable Development Goals (SDG) and our results highlight the contribution ES are making to achieving these goals in our reservoir landscapes. For example, sustainable production of nutritious plant-based foods and regulated agricultural water delivery is helping support farm production and healthy diets, vital to meeting SDG 2 on food security and sustainable agriculture, while supplies of traditional medicinal plants are helping local households stay healthy, essential to achieving SDG 3 on health and ensuring access to affordable medicines. The contribution ecosystems make to HWB is clearly elicited by participants in this study and re-enforces the notion that ES have a fundamental role to play in achieving sustainable development (Costanza et al., 2017; Wood et al., 2018). However, ES and ED are co-produced by ecosystems, infrastructure and society (Boyd and Banzhaf, 2007). Ecosystem management alone will not be enough to ensure HWB outcomes are achieved. It needs to be integrated with management of social, political, and economic interventions to ensure farmers have the capacity and rights to access and use ES, and to mitigate impacts of ED. The reservoirs around which farming activities revolve in our case studies are an example of co-produced freshwater and associated food supplies, whose access is socially mediated and dependent on reservoir governance arrangements.

5.5.3. Shared and conflicting values

While participants widely considered ES and ED of importance for their HWB, several key value differences emerged along socio-economic lines. For example, Mossi people tended to place a lower value on the importance of both ES and ED compared to other ethnic groups. This may simply reflect cultural differences in how natural resources are valued, or it may be associated with Mossi people having relatively good access to different land types and therefore multiple ES, being primary landowners. In contrast, minorities and Kusasi (for agricultural pests) tended to place a higher value on the importance of ED for detracting from HWB compared to other groups. For minorities, this

may be because people have less access to pest mitigation measures, while for Kusasi, who dominate the Ghanaian sites, it is possible that prevalence of agricultural pests is higher in these locations. Future studies would be beneficial to confirm tendencies across ethnic groups and explore possible explanations in more depth.

Our results revealed low levels of agreement among some participants regarding the importance of plant-based foods, meat, fish, agricultural water and desirable flooding which are all ES whose access is mediated by the reservoir. Assigned values for each of these ES were significantly different across two or more socio-economic groups, including household income and self-evaluated health (plant-based foods), ethnicity (fish), household dependency ratio (fish and meat), occupation (meat), age and level of education (agricultural water), gender, occupation, household income, farm area, and time in the community (desirable flooding). Farmers indicated that fish and meat are generally purchased rather than harvested directly from the landscape, despite fish being readily available from the reservoir. Government regulation of fish and meat prices, particularly when these products are produced with water from or sourced directly from the local reservoir, could help provide more even access among households to these foods and minimize potential conflicts or HWB trade-offs related to these ES. However, this would need to be carefully managed to avoid over-consumption of meat or fish. Plant foods, agricultural water and desirable flooding support, or are mediated by, irrigated cropping activities. It is possible that lower levels of agreement for the importance of these ES reflect differing levels of access to irrigable land and water, and/or capacities to turn this access into productive farmland which requires labour, technical and knowledge inputs. Obtaining access to water and irrigable land is likely to become increasingly difficult in the study sites as the youth-heavy population continues to grow while households continue to rely on agricultural livelihoods. Younger and less educated participants, who placed a higher importance on agricultural water for their well-being, may be particularly vulnerable to food shortages if their reservoir water access

or supplies are reduced. They may also be susceptible to conflicts with elder, better educated peers who are more likely to be involved in natural resource management decision processes. Appreciation of flooding among relative newcomers to the community, rainfed and irrigated crop farmers, female farmers with small farm areas and very low incomes, may also reflect a high dependence on flood regimes for agricultural water access, i.e. lack of access to motor pumps and other costly water transportation methods. The timing and extent of these flood regimes are part determined by reservoir management, making it important that reservoir managers continue to try and meet the needs of diverse user groups. In general, the significant differences among socio-economic groups regarding the importance of food and water-related ES is likely to be linked to unequal access to these ES, and therefore difficulty realising the HWB benefits, driven by reservoir governance which is subject to all common-pool resource management challenges (Ostrom, 1999).

In contrast, there was a high level of agreement (no significant differences) regarding the importance of firewood and charcoal and organic fertilizer among men and women, age groups, people with different occupations, education levels, incomes, farm sizes and ethnicities. Shortages of firewood and organic fertilizer are common concerns among farmers in the study sites. Given their cross-cutting importance for cooking (firewood) and food production (fertiliser), future declines in these ES are likely to have direct negative impacts on local health and material well-being. These risks could be mitigated to some extent by, for example, managed tree planting to increase the availability of fuelwood, and promoting soil conservation agriculture where this is not already in use to improve soil health and reduce demand for organic fertilizer.

5.5.4. Implications for reservoir landscape management

Generally most ES and both ED were considered important for HWB by farmers in this study. This calls for a holistic approach to reservoir landscape management which seeks to maintain sufficient supplies of a diversity of ES while minimising trade-offs with ED. Future

research to identify threats to the contribution local ES make to HWB, and to explore how to decrease negative effects of ED, would help distil actions that could be taken to ensure net positive relationships between ecosystems and HWB in reservoir landscapes. Intensifying crop production by introducing reservoirs is an active national policy in both Burkina Faso and Ghana, aimed at closing food supply gaps and boosting rural development. The high importance farmers attributed to multiple ES in this study implies natural resource policies in reservoir landscapes should not focus solely on sustainable water management at the expense of other locally valuable resources. Maintaining multiple ES across the landscape could help minimize tensions and potential conflicts that may arise, such as between reservoir users and non-users. This may also help shield the wellbeing of users of reservoir-mediated ES, which will be negatively impacted by future loss or degradation of these ES as reservoirs inevitably dry up seasonally and eventually permanently (Jones et al., 2017). Since agriculture is the dominant land type in each of our cases, a promising option could be to improve ES supplies from local agroecosystems. As agricultural land is already managed or semi-managed, it is also potentially easier to safeguard, enhance and diversify agro-ecosystem functionality to meet ES demand rather than altering management of other land types (DeClerck et al., 2017). This approach empowers farmers as principal land stewards to shape their own landscape futures (Raymond et al., 2016).

Regarding ED, our results reinforce the notion that mitigation measures to reduce the risk of local farmer exposure to vector borne diseases, notably malaria, should be implemented systematically where reservoirs are present in order to minimize serious negative impacts on farmer well-being. These measures may include education on how to protect against mosquitoes and other vectors, provision of mosquito nets, and increasing local habitat for natural predators such as bats and birds.

5.5.5. Limitations of this study

We collected data on assigned values for ES and ED from a small number (n=37) of farmers relative to the total number of smallholder households in each case study landscape. We chose to limit the survey to only farmers who had participated in the participatory mapping focus groups to ensure a shared understanding of ES and ED concepts and terminology. In addition the farmers were selected by local gatekeepers who may not have selected the most marginalized households in the landscape. As a result, while our sample is representative of a range of ages, ethnicities, education, and income levels, we may not have captured the full spectrum of viewpoints on the HWB importance of ES/ED among smallholder farmers in these landscapes.

Fewer ES were identified in the participatory ES mapping at the Ghana study sites, Binaba and Tanga. This is likely to reflect methodological errors and limitations, i.e. omission of fodder in the pre-determined ES lists and the quality of the translation, rather than lower on-site ES diversity. We discussed the research concepts in depth with each translator prior to data collection. However the translator assisting at the Ghana sites was less comfortable with ES concepts that the translator in Burkina Faso. Descriptions of more complex ES, such as soil moisture retention and desirable flooding, may not have been as clear for participants at the Ghana sites.

5.5.6. Future research priorities

The social valuation approach applied here (i.e. using a simple Likert scale and interview) proved effective at accommodating a broad range of interpretations of how to judge the importance of an ES or ED for HWB. While we focused on the relative importance of ES and ED to HWB, several respondents highlighted that sources of well-being not associated with locally available ES / ED - such as purchased medicines and doctors to treat diseases, bottled gas for cooking fuel – were important for their well-being. Future research that includes direct questions to identify the importance of ES-sources of HWB in relation to

non-ES sources would help distil the contribution ES can make to overall HWB.

Explicitly including ED into the MEA, IPBES and other frameworks for assessing ES and HWB interactions would help ensure future studies applying these frameworks encompass the full diversity of ecosystem-HWB linkages. Suich et al. (2015) show that many studies of ES-HWB linkages fail to include ED in their analyses, yet our results indicate ED can be of high importance for HWB. These negative impacts of ecosystems on HWB, while acknowledged, should be more clearly elicited in the MEA and IPBES typologies and further researched to provide decision-makers with more complete information on ecosystem-HWB linkages.

5.6. Conclusions

This study points out that while there is increased attention towards ES, ED and the contribution ecosystems can make to HWB, more work is needed to elicit and integrate insights to inform sustainable development in reservoir landscapes. Our results highlight specific services, including plant-based foods, domestic and agricultural water supplies, firewood and charcoal, medicinal plants, and soil nutrient cycling (ES), and problems arising from human disease vectors (ED), were consistently identified as of high or very high importance for human well-being by many (>80%) farmers in our case study landscapes. The high importance farmers attributed to multiple ES implies natural resource policies in these reservoir landscapes should seek to maintain multiple ES, and mitigate exposure to human disease vectors, to help minimize tensions and potential conflicts that may arise between reservoir-mediated ES users and non-users. In our study, farmers associated multiple ES with positive health, material, security, social, and happiness outcomes, and ED with negative health and material outcomes. These HWB outcomes are encapsulated in the SDGs, re-enforcing the notion that the contributions ecosystems make to improving HWB should be firmly incorporated into local and national sustainable development planning.

Application of our method in other reservoir landscapes would be valuable to

document the spectrum of farmer viewpoints on the contributions ecosystems make to HWB in these contexts in order to draw more general conclusions of where, when and how ES and ED impact on HWB. With sufficient studies it would be possible to identify consistently important ecosystem-HWB linkages across reservoir contexts and provide general guidance on strategies to manage trade-offs between ES, ED and associated HWB outcomes for local farmers in these landscapes. Since local households have the most to gain or lose from changes to ES and ED in their landscapes and are primary ecosystem stewards, assessments of ES and ED that integrate local perceptions and value judgements should be widely deployed to help identify locally appropriate policies and incentives for sustainable ecosystem management and development planning.

Acknowledgements

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6. Discussion

Interventions to sustainably intensify smallholder crop production are key to meeting future food demand and improving farmer well-being in the Volta basin, where an estimated 70% of farms are smallholdings (Deininger and Byerlee, 2012), population is increasing at 2.7% per year across the six Volta basin countries, and 11-64% of people live in severe poverty (UNDP, 2016). This thesis focused on understanding the socio-economic and environmental conditions under which community-managed reservoirs can effectively and sustainably increase dry season cropping and local farmer well-being in the Volta basin. To answer this question, Chapters 2 and 3 focused on closing key data gaps regarding reservoir water and dry season irrigated cropping dynamics focusing on small (< 1m3) and medium (1 – 10 Mm^3) sized reservoirs, which tend to be community-managed. Chapter 4 assessed the socio-economic and environmental factors associated with dry season cropping at small and medium sized reservoirs, and the environmental sustainability of this irrigation in terms of water productivity. Chapter 5 used in depth work at four community-managed reservoirs to characterize farmer well-being outcomes through an ecosystem service lens and implications for sustainable reservoir landscape management.

There are four overarching findings. First, reservoir locations, dynamics and their irrigation uses can be reliably documented using open access earth observation imagery, opening up opportunities for improved dam impact monitoring and evaluation. Second, the Volta basin contains 1200 reservoirs of which 96% are small or medium sized, yet only 46% of these reservoirs are effective in terms of leading to increases in dry season crop production. Small and medium sized reservoirs are more likely to be used for dry season irrigated cropping if their locations and design match specific socio-economic and environmental factors, with implications for future reservoir intervention planning. Third, environmental sustainability of dry season irrigation, as measured by crop water productivity, is highly variable and could be improved at many reservoirs.

Fourth, different farmers rely on different ES in the case study reservoir landscapes, and associate multiple ES and ED with each dimension of HWB. Maintaining a diversity of ES in each of these landscapes, and taking stronger action to mitigate the effects of ED, is likely to generate more sustainable outcomes for farmer well-being.

Subsequent sections discuss how these results contribute to knowledge of the impact of community-managed reservoirs on crop production and HWB in the Volta basin, and of how to improve the uptake and sustainability of dry season irrigated cropping at these reservoirs. I draw out possible consequences of the findings for practitioners and identify future research priorities.

6.1. Monitoring and evaluation of reservoir interventions

Monitoring dams and evaluating their impact is fundamental to adaptive learning and, in the long-term, improving the overall sustainability and development effectiveness of these investments. Vast sums of money are spent to support rural agricultural development. Monitoring and evaluation helps improve transparency and make governments and aid organisations accountable for expenditure of public funds (Piirainen, 2014). Despite a century of investments in small dams in the Volta basin, and each new dam costing approximately \$20,000 to \$400,000[9] (Venot et al., 2012), locations and sizes of small and medium sized reservoirs are inconsistently documented and there are no publicly available records of their investment costs, long-term impact or outcomes.

Chapter 2 developed and demonstrated a semi-automated approach for mapping reservoir locations and surface areas through time in the Volta basin, using surface water maps created with freely available earth observation tools and data. Results showed there were 1200 active reservoirs as of 2015, *i.e.* those containing water for at least part of the year, of which 1055 were small (<1 Mm^3), which is broadly

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[9] Based on costs of small reservoir investments in Upper East, Ghana

consistent with official estimates of reservoir numbers. For example, the Direction Générale des Ressources en Eau's official records for 2011 showed 719 of Burkina Faso's small dams were situated inside the Volta basin, while Venot et al. (2012) report that there were 536 small dams in Ghana in 2010 based on official data with most dams located in the Upper East and Upper West regions and thus within the Volta basin. The limitation of these official records is that the locations of reservoirs are often not recorded accurately and, for many reservoirs, there is no or limited information available on reservoir volumes and other information such as reservoir uses. The added value of the new reservoir dataset compiled in this thesis is that the locations and sizes of reservoirs are consistently documented across the entire basin, providing a baseline for monitoring and evaluation. The semi-automated reservoir mapping approach used to derive this dataset can be readily and relatively cheaply re-applied periodically to update information as reservoirs dry up and new ones are built, providing a practical approach to reservoir monitoring. It can also be applied elsewhere around the globe to close gaps in knowledge regarding the worldwide distribution and sizes of small reservoirs (Wisser et al., 2010).

Applying the semi-automated method to mapping reservoirs to the Global Surface Water map (Pekel et al., 2016) showed that estimates of reservoir surface areas were 19% less accurate than those derived from the best performing surface water map created in this study by applying standard water indices to Landsat 8 OLI imagery. The relatively poor performance of the Global Surface Water map for mapping reservoir extents is consistent with other emerging studies (Ogilvie et al., 2018). Errors in the Global Surface Water based estimates made these unreliable for assessing surface areas or seasonal dynamics of reservoirs whose areas change by 5.1 ha or more during a given year. This result is significant since the Global Surface Water dataset is freely available and use of these data for agricultural water resource management without knowledge of information uncertainties could have serious repercussions. A safe approach identified in Chapter 2, to ensure reservoirs are not omitted from the analysis

or falsely identified as dry, is to apply integrated methods to reservoir monitoring that combine manual digitisation from high resolution imagery with automated surface water extraction from lower resolution imagery, and to limit seasonal analyses to larger reservoirs. Future applications of this integrated approach to mapping small reservoirs could explore the use of Sentinel 2 imagery, which produced small reservoir surface area estimates with a higher accuracy than estimates from Landsat imagery in Ogilvie et al. (2018).

Understanding the impact of community-managed reservoirs on local food production, once their location is known, requires information on agricultural uses of reservoir water. While several previous studies have successfully used remote sensing to map large, mono-cropped irrigated fields (Rufin et al., 2018; Salmon et al., 2015; Wardlow and Egbert, 2008), studies of mixed cropping systems in small fields are currently under-represented in the literature. This is a significant gap given that small (<2 ha) farms dominate Africa, Central America and much of Asia (Deininger and Byerlee, 2012). Chapter 3 tested three approaches to using vegetation indices for automated delineation of dry season irrigated areas proximate to reservoirs, on Landsat 8 OLI and Sentinel 2 MSI imagery. None of the methods tested proved satisfactory, highlighting the need for future research and/or technological advances to help close this data gap. However, Chapter 3 showed that manual approaches to delineating irrigated cropland using Google Earth Pro imagery are a viable alternative and likely the most reliable option until such time that automated approaches prove more effective. Applying this manual approach to the Volta basin revealed that dry season irrigation occurs at 46% of the 1155 small and medium sized reservoirs. The total irrigated areas is 5588 ha, with a mean irrigated area of 10.6 ha per reservoir. Chapter 4 discusses the implications of this and demonstrates irrigation at small reservoirs is likely to benefit, on average, 22 households per reservoir, rising to 133 households at medium sized reservoirs, and totalling 22,352 households across the Volta basin. The number of beneficiary

households is small considering the significant cost of building community-managed dams. For example, using the most conservative cost estimate ($20,000) from Venot et al. (2012), total investment in the Volta basin's small reservoirs amounts to $23,100,000, or $1033 per dry season irrigating household.

Chapter 3 also showed the area irrigated upstream is larger than the downstream irrigated area at many reservoirs, consistent with previous research (Venot et al., 2012). This result suggests many communities face challenges with enforcement of reservoir water management regulations, since irrigation is normally planned downstream of a reservoir. Upstream irrigation provides easier access to water where no downstream irrigation scheme has been constructed, and can be many times more profitable than downstream irrigation (Venot et al., 2012). However, widespread upstream irrigation is likely to cause environmental problems and reduce the lifetime of downstream reservoirs, since eroded soil and agrochemicals from these plots run directly into the stream network. These negative effects could be mitigated by interventions to encourage agroecological farming practices - replacing external inputs with natural processes (Miguel A Altieri et al., 2012) - in upstream irrigated areas, such as introducing hedgerows or grass strips at the base of irrigated plots to capture sediment, and using disease-resistant crop varieties or planting bird and insect habitat within or adjacent to plots to boost natural pest controls and avert the need for pesticides.

Interventions to strengthen local reservoir governance structures could also help reduce upstream irrigation by empowering communities to set, monitor compliance and enforce regulations (Birner et al., 2010). This could include, for example, providing community-exchange opportunities between poor and well managed reservoirs; supporting the formation of inclusive and representative community-level water user associations (Ghana) or local water committees (Burkina Faso) at reservoirs where these are not yet established or not functioning, and; providing communities with the tools and knowledge to monitor their own reservoir resources (inter-annual water dynamics,

sectoral water withdrawals, water quality) and thus make more informed management decisions.

6.2. Towards improved reservoir effectiveness

As with many rural development interventions, there is a risk that dam interventions are deployed in a fairly uniform manner worldwide without adjustments for context dependent knowledge or expertise, and are expected to produce similar results (Escobar, 1995, p.146). Interventions to improve agricultural water supplies with little attention as to how benefits and costs are distributed can increase social inequalities, widening the gap between rich and poor farmers and further marginalising the poorest. For example, the high spatial and seasonal variability in reservoir water supplies demonstrated in Chapter 2 flags that there are unequal opportunities for farmers to intensify cropping systems through dry season irrigation, which may be deepening the poverty and food security divide between farming landscapes with and without reservoirs.

Irrigation is promoted as a poverty alleviation tool for smallholder farmers in sub-Saharan Africa (Burney and Naylor, 2012), yet in a study on the linkages between agricultural water availability and poverty in the Niger basin, (Ogilvie et al., 2010, p.614) found that “poverty prevails in areas of good soil quality, high productivity and sufficient available water”. The relatively low adoption of dry season irrigation at Volta basin reservoirs identified in this thesis indicates that many small and medium sized reservoirs are not leading to increased crop production and the associated benefits for smallholder farmers. This is a warning sign for development investors and regional policymakers seeking to address the basin’s food production challenges, and Volta basin countries who have committed to further dam investments in the coming years with the aim of promoting irrigated cropping. Chapter 4 identified a core set of socio-economic and environmental factors associated with irrigated cropping activity that could be used to improve targeting of future dam interventions to increase the chances that they

effectively boost dry season crop production. Specifically, irrigation at the basin's small and medium sized reservoirs was found to be significantly more likely where reservoirs have better water availability (larger volumes, higher runoff rates, fewer dry months), better local market access (proximity to towns), greater pressure on local water resources (higher population and cattle densities, poorer water quality), and where there are marginally fewer human resources available (slightly lower labour availability and literacy rates). The latter factor may reflect differences in demographics and education levels between rural and urban areas, and thus indicate irrigation is more likely in rural landscapes where agricultural livelihoods dominate, but further work is needed to confirm this hypothesis.

While there are a few sub-national and micro studies of factors associated with irrigation (Birner et al., 2010; Wekem, 2013), this is the first study to test the significance of socio-economic and environmental factors for the whole population of small and medium sized Volta basin reservoirs. Ensuring factors conducive to irrigation are in place when investing in community-managed reservoirs would help make these investments more effective. The need to more carefully target irrigation developments to local contexts is likely to become more pressing as climate change, increasing food and water demand, make unproductive irrigation systems a threat to sustainable development (Turral et al., 2011). Knowledge of how context impacts on reservoir performance can also be used to identify where technical, social or economic interventions could be planned at existing dams to create a more enabling environment for irrigation uptake.

6.3. Towards improved sustainability and well-being outcomes

Chapter 4 showed that crop water productivity of dry season irrigated areas could be improved at an estimated 74% of small and medium sized reservoirs, where the ratio of irrigated cropland area to irrigation water use was lower than at the best performing reservoirs. Increasing water productivity at these reservoirs would improve outcomes by enabling more farmers to benefit and/or raising incomes for existing

irrigators. Water productivity could be increased by improving irrigation water management to reduce water use, enhancing soil infiltration rates and reducing runoff (e.g. with crop residues, organic fertilizer, conservation tillage), and switching to crops that consume less water. Such increases in water productivity would help save water, make it available for use by other irrigators or sectors, and help close yield gaps (Jägermeyr et al., 2016). Of note, results from Chapter 4 show there was a strong relationship between crop water productivity and reservoir size and shape. Water productivity was highest at reservoirs with volumes smaller than 157,597 m^3. This may reflect scarcer water resources leading to more careful water management and suggests there are sustainability benefits of investing in smaller over larger community-managed reservoirs. However, reservoir water scarcity is a potential source of conflict in the region (Ayantunde et al., 2018), so caution is needed before policy decisions are made based on this result.

While Chapters 2 and 3 demonstrated the feasibility and value of remote sensing approaches to reservoir monitoring, reservoirs need to be studied at finer spatial scales to understand impacts on individuals and communities. Chapter 5 presented work in four case study sites to understand farmer perceptions of ecosystem-related benefits in their reservoir irrigated landscapes. Across the four case study sites farmers identified a diversity of ES that contribute to each dimension of HWB. This is consistent with theoretical framings of the linkages between ES and HWB (Díaz et al., 2015; IPBES, 2013; MEA, 2005). This result highlights the importance farmers attribute to ED and their negative impact on HWB, supporting calls to better incorporate these into ecosystem service assessments to illuminate trade-offs of land management decisions (von Döhren and Haase, 2015). A potential limitation of Chapter 5 is that a rating approach was used to obtain the ES and ED value measures. When individuals are not forced to make a choice about the value of one item compared to another, there is a risk that the assigned scores fall within a narrow range (Feather, 1973). The prevalence of ‘high’ and ‘very high’

importance ratings in this study is likely to be an artefact of this. On the other hand, each of the case studies is home to natural resource dependent communities who can be expected to attribute equal importance to a diversity of contributions ecosystems make to their well-being, particularly given the interdependence of some ecosystem services (e.g. fuelwood used for cooking, and food). Using a ranking approach may therefore result in participants artificially differentiating the importance levels of ES and ED. Moreover, research has shown that the aggregate order of items is generally similar under both rating and ranking approaches (Feather, 1973; Moors et al., 2016) and the construct validity of the two measures is similar (Rankin and Grube, 1980). This suggests that rating and ranking may be used interchangeably for purposes of comparing median values across groups (Alwin and Krosnick, 1985), as was the case in this thesis.

An original dimension of this thesis is it breaks down the dimensions of HWB in relation to ecosystems and their relative importance at the local level using a social valuation approach. This approach was effective at documenting farmer perceptions of the importance of ecosystems for HWB in four rural landscapes with relatively low market interaction, where monetary valuations can be challenging and irrelevant (Christie et al., 2012). The study contributes to addressing the recognized lack of non-monetary and particularly social valuations of ES in Africa (Wangai et al., 2016) and in dryland and poverty contexts (Suich et al., 2015). Results highlighted value differences between socio-economic groups of farmers that can inform resource management aimed at improving equity in HWB outcomes in the case study sites. Inter-group differences in values, for example along gender, age, education and income lines, support the notion that ecosystem service assessments need disaggregating to the individual level in poverty contexts (Daw et al., 2011) because what is very important for the well-being of one person or group may be of little significance to another. Disaggregation highlights trade-offs that are likely to be masked at higher levels.

6.4. Conceiving reservoirs as part of socio-ecological systems

Results of this thesis suggest that reservoirs should be viewed, planned and managed as part of the socio-ecological systems and not as isolated built infrastructures. Reservoirs are interconnected through people and ecosystems with their upstream catchments, downstream waterways, and surrounding landscapes. Reservoirs can be conceptualised as temporary end points or “hubs” for hydrological ES produced in upstream areas and made accessible to farmers and other water users through the presence of the reservoir. Hydrological ES, also known as water-related ES, “encompass the benefits to people produced by terrestrial ecosystem effects on freshwater” (Brauman et al., 2007). These include processes such as flow regulation and erosion control provided by natural systems and well-managed agricultural systems, that help maintain supplies of freshwater in the reservoir. The capture and regulation of reservoir water supplies is heavily dependent on other factors as well, including reservoir capacity, design, management, catchment size, and local climate. Reliable reservoir water supplies benefit local households who use this water for irrigated crop production and other purposes, but the presence of reservoir water proximate to habitat suitable for certain vectors, notably mosquitos, brings water-borne diseases and negative impacts to these same households. (Figure 29). These negative impacts, referred to as ED, have received much less attention that ES in research (Campagne et al., 2018). Chapter 5 of this thesis clearly shows ED are a significant problem for local well-being and need incorporating into reservoir planning.

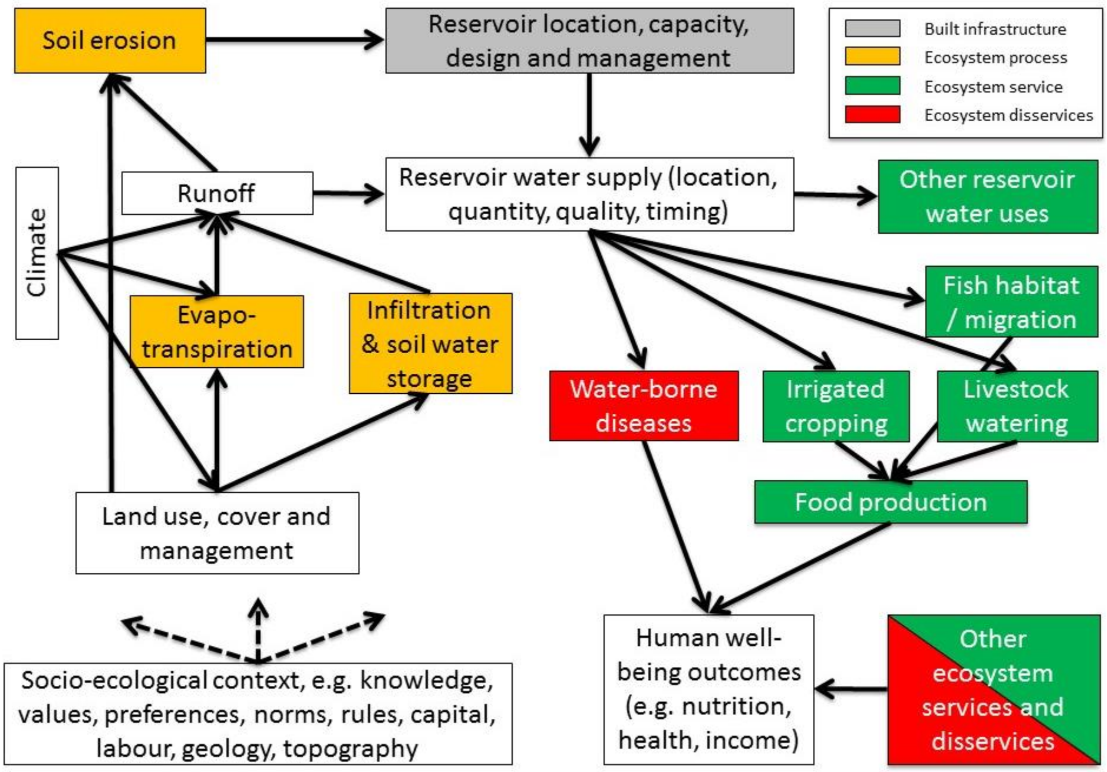

Figure 29: Conceptualisation of how ecosystem services flow through small reservoirs to benefit people, and feedbacks from land use, cover and management choices on upstream land. Socio-ecological contexts influence the provision, delivery and distribution of services and disservices from the reservoir and surrounding landscape.

Chapter 5 also showed that ES mediated by reservoirs (agricultural water, domestic water, desirable flooding, irrigated crops, fish and livestock water) were not considered by farmers as significantly more important than other locally available ES, in the four case study sites. In community-managed reservoir landscapes, farmers retain dependencies on several types and sources of ES for their well-being. This result is important as it implies that reservoirs are more likely to provide lasting benefits to HWB for multiple smallholders where there is access to a diversity of ecosystem benefits in the landscape beyond agricultural water.

Making irrigation at community-managed reservoirs more beneficial in terms of HWB outcomes may therefore be best approached by recognising reservoirs are part of larger socio-ecological systems. Conserving upstream areas that helps maintain hydrological ES, such as natural grasslands and well-managed farmland that help control sediment, may prolong the lifespan of a reservoir; and reduce maintenance costs. Yet

trade-offs with other landscape benefits need careful attention to maintain other locally important sources of well-being that famers continue to rely on after a dam is built. ED associated with reservoirs also need to be mitigated to the extent possible to ensure overall net benefits to local HWB.

6.5. From science to practice

This thesis provides several methods for remote monitoring of community managed reservoirs, notably to track reservoir locations, water dynamics and associated irrigation activities. These methods are based on freely available tools and datasets and could be adopted by water managers and agricultural policymakers in the Volta basin and beyond to improve dam monitoring and evaluation. Use of the approach for tracking reservoir surface areas presented in Chapter 2 should favour use of the MNDWI over the GSW and restrict the analysis to reservoirs whose extents change by < 3.0 ha (or >5.1 ha if using GSW) to ensure reliable results.

Chapter 4 provides practical recommendations on reservoir placement and design which can be used to guide future investments in community-managed reservoirs in the Volta basin. Irrigation is significantly more likely at reservoirs with favorable socio-economic and environmental conditions. In particularly, irrigation is more common at reservoirs with relatively large volumes; mean reservoir volume at irrigated reservoirs was 598,439 m^3 and at reservoirs not used for irrigation the mean volume was 35,544 m^3. Conversely, environmental sustainability of this irrigation in terms of crop water productivity improved with decreasing reservoir volume and the most sustainable reservoirs had mean volumes of 66,737 m^3, while the least sustainable had mean volumes of 753,534 m^3. This suggests that designing reservoirs with a capacity between 35,544 m^3 and 753,534 m^3 is a promising option to promote more environmentally sustainable dry season irrigated cropping. Ensuring other socio-economic conditions favorable to irrigation are in place as well, such as proximity to towns (< 18.7 km) and sufficient population densities (>105 persons per km^2), should help secure this outcome.

Results showed that irrigation is significantly more likely in areas with lower literacy rates and lower labour availability, yet caution should be taken before operationalizing this finding into policy since it may simply represent a rural-urban divide between education levels and demographics. At existing reservoirs, the environmental sustainability of irrigated cropland would be improved by interventions to increase crop water productivities focusing on reservoirs which currently have relatively low productivities. For example, non-governmental organizations or government institutions could provide training and incentives to farmers to plant dry season crops with lower water requirements, improve soil conservation practices to increase soil moisture retention, and conserve reservoir water by optimizing irrigation schedules.

Case study work in Chapter 5 indicated there are real gains to be made for farmer well-being in considering how supplies of reservoir water for irrigation can be sustained alongside conserving or improving the supply of other locally important ES, and mitigating ED. Ecosystem service management usually requires collective action which brings together social actors from multiple places and institutions (Barnaud et al., 2018). Landscapes are the appropriate scale for interventions to manage ES (Geertsema et al., 2016; Tscharntke et al., 2012) as they encompass ecosystem processes operating at different spatial and temporal levels (Hein et al., 2006; Power, 2010). A landscape approach can help coordinate the natural, social, human and economic capital required to bring about changes in ecosystem service management (Costanza et al., 2017).

This thesis reinforces the notion that policy actions to better manage ecosystems for HWB outcomes will require participatory approaches that seek to understand and incorporate local perspectives and concerns into decision-making processes. Relationships between ecosystems, ES and HWB are intrinsically complex (Norgaard, 2010). Ecosystem service management involves trade-offs, where the production and use of one ecosystem service leads to a decline in another, such as harvesting forest timber causing a decline in bird habitat and natural pest control

services. This means there are winners and losers (and those who experience no change) in any ecosystem management decision, making these decisions social processes that should involve collective negotiation (Barnaud and Antona, 2014). Ensuring local engagement with reservoir construction and landscape management will help highlight values, concerns and knowledge held by local households that can inform planning decisions and minimise trade-offs in HWB particularly for vulnerable groups.

6.6. Future research priorities

Chapter 3 highlighted challenges with automating remote detection of smallholder irrigated cropland in the Volta basin, using Landsat 8 OLI or Sentinel 2 OLI imagery. Smallholder farms are characterised by small field (often <1 ha) and mixed cropping systems making it hard to separate cropland from other land use and cover types. Yet basic monitoring of reservoir impacts on crop production requires knowledge of where irrigated cropping is happening. Such data can inform national, regional and even global assessments of irrigation water use. Future research should focus on developing methods for automatic detection of smallholder irrigated cropland to help close this gap. This could include, for example, exploring the use of Sentinel 1 synthetic aperture radar data to detect crop growth periods; testing the use of very high (<2 m) resolution imagery; and integrating object-based classification methods for detecting irrigated cropland where this is practiced inside linear field boundaries.

This thesis shows there is scope to increase irrigation adoption at small and medium sized reservoirs in the Volta basin, yet it is important to recognize that dam interventions are a time-limited solution to boosting food production and through that, farmer well-being. The temporary economic benefits they provide to farmers may be sufficient to propel some households out of poverty, transforming lives. But if they are not transformative, increasing livelihood dependency on reservoirs may act to make farmer livelihoods more vulnerable and create or deepen poverty traps. Case study work around four reservoirs in Chapter 5 showed local farmers place a high importance on

agricultural water from reservoirs for nutrition and income. It remains unclear whether irrigation at community-managed reservoirs results in meaningful improvements in smallholder well-being over the long-term. This is partly because of a lack of studies linking irrigated cropping to HWB outcomes, such as nutrition and social relations (Domènech, 2015). Impacts on income are better studied but remain inconclusive. A review of linkages between irrigation and poverty across Asia concluded that small-scale irrigation strongly benefits the poor by increasing overall production, yields, employment and wages, household income, and reducing risk of crop failure (Hussain and Hanjra, 2004). However, benefits are reduced where there is corruption, poor irrigation infrastructure design, insufficient irrigation water, inequity in land and water resource management, and poorly managed externalities such as impacts on downstream water. In contrast, (Ogilvie et al., 2010) found a weak relationship between dams and poverty levels across the Niger basin, and concluded that either irrigation at its current extent is having a negligible impact on poverty or the impact is not detectable at their basin-wide scale of analysis. Namara et al. (2010) argue that dams can exacerbate local poverty levels by creating environmental problems that hamper production, such as waterlogging, and causing declines in health though increased transmission of waterborne diseases. Future research on the long-term effects of reservoir irrigation and HWB outcomes in the Volta basin would be valuable to help determine whether dam investments are transformative food production and development devices.

Research for this thesis took place in the Volta basin and community-managed reservoirs exist in many other sub-Saharan Africa and semi-arid settings. Comparative studies of which socio-economic and environmental factors are associated with small and medium sized reservoir irrigation in different contexts would be helpful to build a more comprehensive picture for investors and communities. Similarly, comparative qualitative research to disentangle farmer perceptions of the importance of ecosystems for HWB in other reservoir contexts would be valuable to identify more general

conclusions regarding linkages between ecosystems and HWB in such contexts. With enough studies, it should be possible to detect consistently important ecosystem-HWB linkages in reservoir-irrigated landscapes and identify a set of potential ecosystem service management approaches that would sustainably improve HWB outcomes for farmers.

Finally, tackling multi-disciplinary and cross-scale problems, like sustainable food production and ecosystem service management, is never easy. Yet these are among the most pressing challenges we as a research community need to try and resolve, with local stakeholders, if we are to enable evidence based decision-making for sustainable outcomes in the real-world. There are many research approaches that could be taken in order to respond to the question of when, where and how more food can be sustainably produced through reservoir irrigation. I chose to study this problem at the regional and landscape levels. Future research to identify leverage points that motivate and enable farmers to implement more sustainable irrigation activities at the field and farm level would be a valuable complement.

7. Conclusion

Many smallholder farmers in the Volta basin produce relatively little, making it difficult for them to harvest sufficient quantities of nutritious food, save and scale production. Without intensifying their food production, smallholders are likely to remain in poverty, prone to nutrition-related health problems and lacking sustainable sources of income. Irrigation is a promising form of intensification for those parts of the basin where water limits production. Irrigation needs to be implemented and managed sustainably to maximise benefits for present and future generations of farmers.

In this thesis, I developed methods for monitoring reservoir interventions and dry season irrigated cropping across the Volta basin drawing on Google Earth Engine and freely available satellite imagery, providing practical and robust approaches for monitoring and evaluation of regional reservoirs going forward. Application of these monitoring methods revealed that less than half (46%) of the 1055 small and medium sized reservoirs in the Volta basin are effective in terms of leading to dry season irrigated cropping. Total dry season irrigated cropland associated with these reservoirs amounts to 5588 ha. Analysis of covariates and in depth case study work provided evidence of the socio-economic and environmental factors associated with making small and medium sized reservoir interventions effective in terms of irrigation adoption, and more sustainable in terms of both increased water productivity and the distribution of benefits and costs to farmer well-being.

Dams will continue to divide opinion with their potential to increase food production and local income at the cost of social inequities, conflicts, health impacts, and environmental degradation. The solution is not to halt all investments in dam infrastructure, since these remain important interventions to alleviate water constraints to food production in seasonally dry, agronomic areas. Rather, ecosystems and their services in the surrounding landscape need to be much better integrated into dam design and management to mitigate negative impacts and secure more equitable and

sustainable human well-being benefits for local households.

8. References

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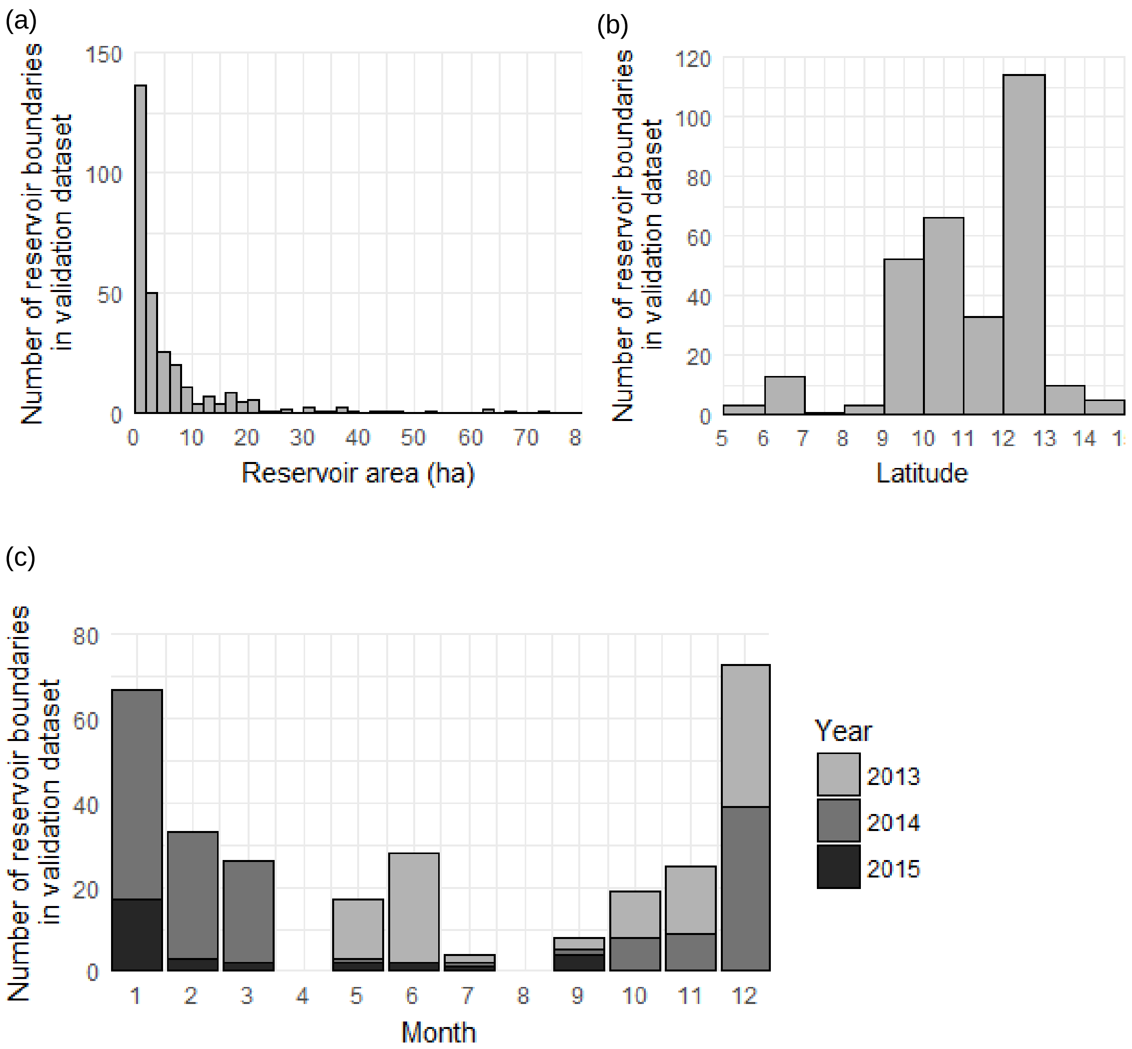
9. Appendices

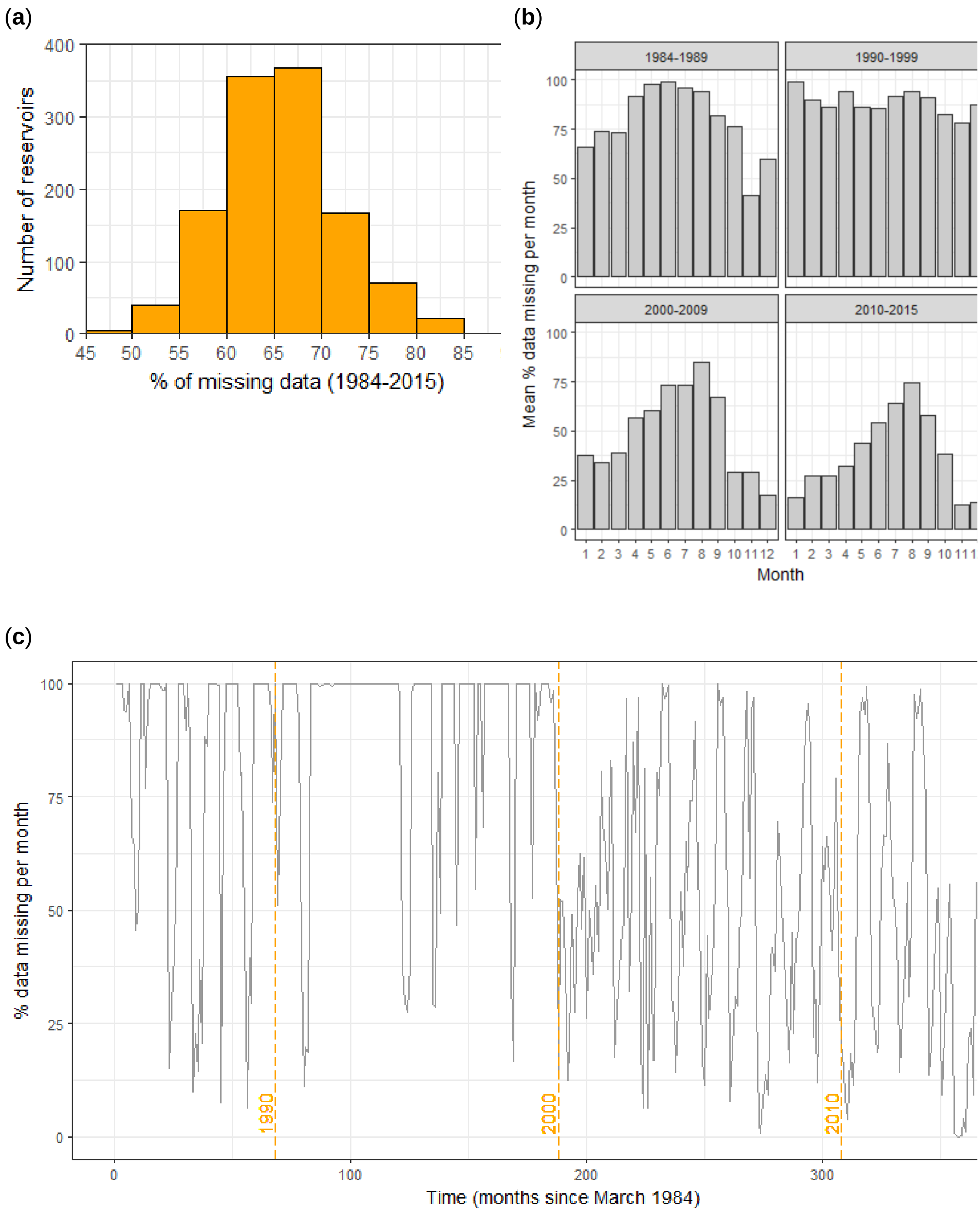
Appendix A

Figure A1: Google Earth derived reservoir areas data (n = 272), used as validation to assess accuracy of GSW and Landsat 8 OLI reservoir area estimates, distributed by (a) reservoir area, (b) reservoir latitude, (c) imagery month and year used to digitize reservoir boundary.



Appendix B

Figure B1: Data gaps in GSW-MH derived monthly reservoir area estimates for 1200 Volta basin reservoirs by (a) percentage of missing data for each reservoir, (b) mean percentage of missing data for each reservoir per month for each decade, and (c) percentage of reservoirs missing data for individual months.



Appendix C

Table C1. Accuracy of reservoir area estimates (n = 272) derived from Landsat 8 OLI imagery across the 11 thresholds tested for NDWI, MNDWI1 and MNDWI2. Highlighted rows represent optimal thresholds, i.e., those with the lowest mean absolute percentage error for reservoir area estimates.

Method	Threshold	Mean Error (ha)	SD (ha)	RMSE (ha)	RMSE (m^3)	MAE (ha)	MAE (m^3)	MAPE (% Area)	MAPE (% Volume)
NDWI	−0.2	−2.10	3.46	4.04	35,604.71	2.35	16,325.01	64.36	69.63
NDWI	−0.3	0.18	5.20	5.19	50,983.33	2.33	16,097.32	80.94	170.03
NDWI	−0.1	−3.25	4.72	5.72	58,641.61	3.30	26,624.84	75.92	79.38
NDWI	0	−4.19	5.83	7.17	81,063.24	4.20	37,658.41	85.93	88.36
NDWI	0.1	−5.35	8.41	9.95	129,900.56	5.35	53,278.05	92.77	94.28
NDWI	0.2	−6.28	10.14	11.91	168,116.85	6.28	67,039.37	97.21	97.84
NDWI	0.3	−6.87	11.43	13.32	197,431.62	6.87	76,284.01	99.24	99.42
NDWI	0.4	−7.05	11.70	13.64	204,164.64	7.05	79,058.93	99.87	99.92
NDWI	0.5	−7.09	11.80	13.75	206,626.22	7.09	79,844.29	100.00	100.00
NDWI	−0.4	28.00	39.07	48.01	1,245,499.69	28.98	603,229.78	4025.68	49,456.09
NDWI	−0.5	64.76	37.03	74.56	2,344,505.15	65.06	1,927,217.86	7244.77	84,773.09
MNDWI1	−0.3	−0.28	2.62	2.63	19,241.17	1.43	7989.78	56.81	123.11
MNDWI1	−0.2	−1.32	2.64	2.95	22,581.41	1.68	10,085.23	51.17	58.30
MNDWI1	−0.1	−2.29	3.58	4.25	38,206.12	2.45	17,316.77	63.29	68.82
MNDWI1	0	−3.15	4.71	5.66	57,726.14	3.21	25,599.05	73.34	77.38
MNDWI1	0.1	−4.16	6.88	8.02	95,314.52	4.19	37,427.90	81.80	84.90
MNDWI1	0.2	−5.16	9.33	10.64	143,043.85	5.18	50,788.42	88.38	90.61
MNDWI1	0.3	−5.75	9.90	11.43	158,542.46	5.76	59,134.43	92.56	94.04
MNDWI1	0.4	−6.47	11.21	12.93	189,063.76	6.47	69,929.69	96.03	96.91
MNDWI1	0.5	−6.71	11.50	13.29	196,860.03	6.71	73,649.05	97.77	98.23
MNDWI1	−0.4	3.82	13.17	13.69	205,231.30	4.24	38,102.16	497.09	5788.66

Method	Threshold	Mean Error (ha)	SD (ha)	RMSE (ha)	RMSE (m^3)	MAE (ha)	MAE (m^3)	MAPE (% Area)	MAPE (% Volume)
MNDWI1	−0.5	35.12	39.54	52.83	1,429,033.43	35.18	796,790.10	4424.54	55,829.47
MNDWI2	0	−1.33	2.78	3.08	24,040.58	1.75	10,704.68	52.74	60.11
MNDWI2	0.1	−2.30	3.56	4.23	38,001.46	2.45	17,381.79	64.08	69.66
MNDWI2	−0.1	0.10	4.39	4.39	40,035.31	1.77	10,841.12	74.68	200.54
MNDWI2	0.2	−3.21	4.97	5.91	61,382.62	3.29	26,462.21	74.09	78.32
MNDWI2	0.3	−4.73	8.99	10.15	133,549.18	4.77	45,100.89	83.62	86.37
MNDWI2	0.4	−5.40	9.67	11.06	151,062.42	5.41	54,122.27	89.85	91.70
MNDWI2	0.5	−6.11	10.28	11.94	168,735.67	6.11	64,469.66	94.60	95.68
MNDWI2	−0.2	3.74	14.56	15.01	234,362.69	4.40	40,225.86	560.81	8282.32
MNDWI2	−0.3	14.44	27.85	31.32	674,344.73	14.60	225,195.18	1568.41	18,858.55
MNDWI2	−0.4	55.46	38.07	67.23	2,020,361.07	55.50	1,534,017.70	6123.54	71,805.25
MNDWI2	−0.5	84.73	12.88	85.70	2,863,350.91	84.73	2,817,038.71	10,128.18	118,618.67

Appendix D

I used the following protocol for focus groups conducted to gather information on crop type, distribution and management practices for Chapter 4.

Focus group on crops: which, where, when and why

Participants: contact extension workers in advance for help identifying participants.

- We would like 6-10 men and 6-10 women, from different families.
- Aged 18-60, but spread of ages.
- Who farm in different regions of the dam watershed, including irrigated and rainfed.

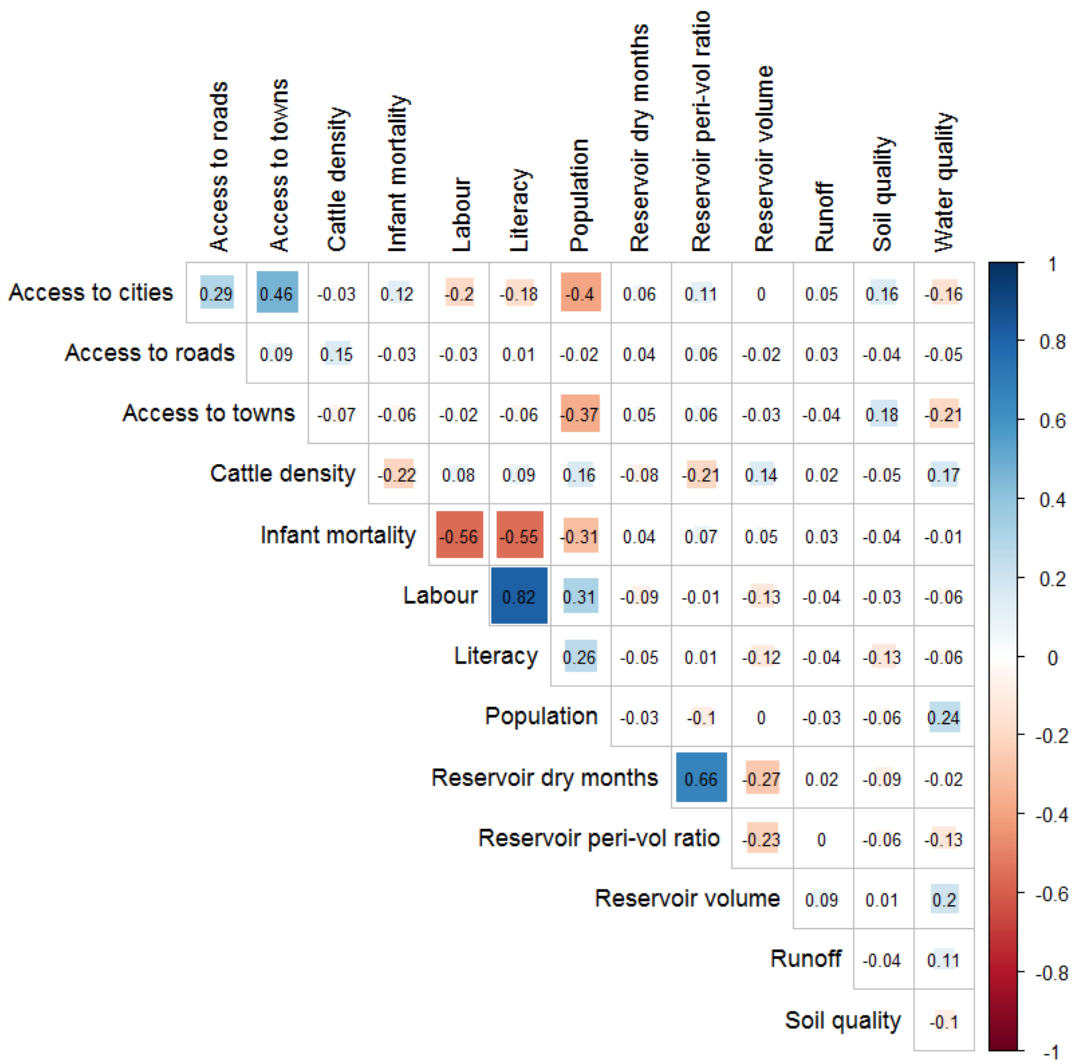
Materials required: maps x 2 of each community laminated, pens to write on laminate, several large sheets of paper, different coloured post-it notes, felt-tip pens.

Duration	Questions/theme	Method
15 mins	Which crops do you cultivate?	Flip chart – list of crops and pictures associated.
15-20 mins	Familiarisation with map	Identify main features on map. Get participants to identify where they live and where they farm.
45 mins	Where do you cultivate crops in the main (rainy season) cropping season?	Post it notes on maps on ground. Participants write or draw which crops they plant and put on map. This gives rainy season crop distribution.
30mins	Which crops do you cultivate and where in other cropping seasons?	Redraw map. This gives dry season irrigated crop distribution.
45mins	Discussion on decision processes. Why do you plant X here? Why do you not plant it there? Why do you plant those crops together?	Draw on map with laminate pens when location-based reasons (sacred forest, distance from water etc) are described to indicate spatial limits of this. Take notes especially on why some crops are irrigated and others not. Listen for local land use names. Prompts if needed: soil type, distance to water, flood regime, topography, preference, regulations.
45mins	Management practices associated with different crops	Post-it notes for each crop placed on scale on flipchart. Activity is for group to agree on ratings of crops from high to low with respect to each management activity, e.g. fertilizer use. Output will be matrix of crops against fertilizer, irrigation water, pesticide, economic value (including consumed/sold), community value (nutrition, culture).

Appendix E

Figure E1 shows correlations between socio-economic and environmental factors used in the irrigation activity analysis (Chapter 4). Figure E2 and Tables E2.1 and E2.2 provide scree plots, correlation matrix statistics, and eigenvectors from the principal component analysis of socio-economic and environmental factors potentially associated with irrigation presence-absence. Figure E3 and Tables E3.1 and E3.2 show equivalent results for the principal component analysis used in the irrigation sustainability assessment.

Figure E1: Correlations between factors used in the assessment of how context influences irrigation activities.



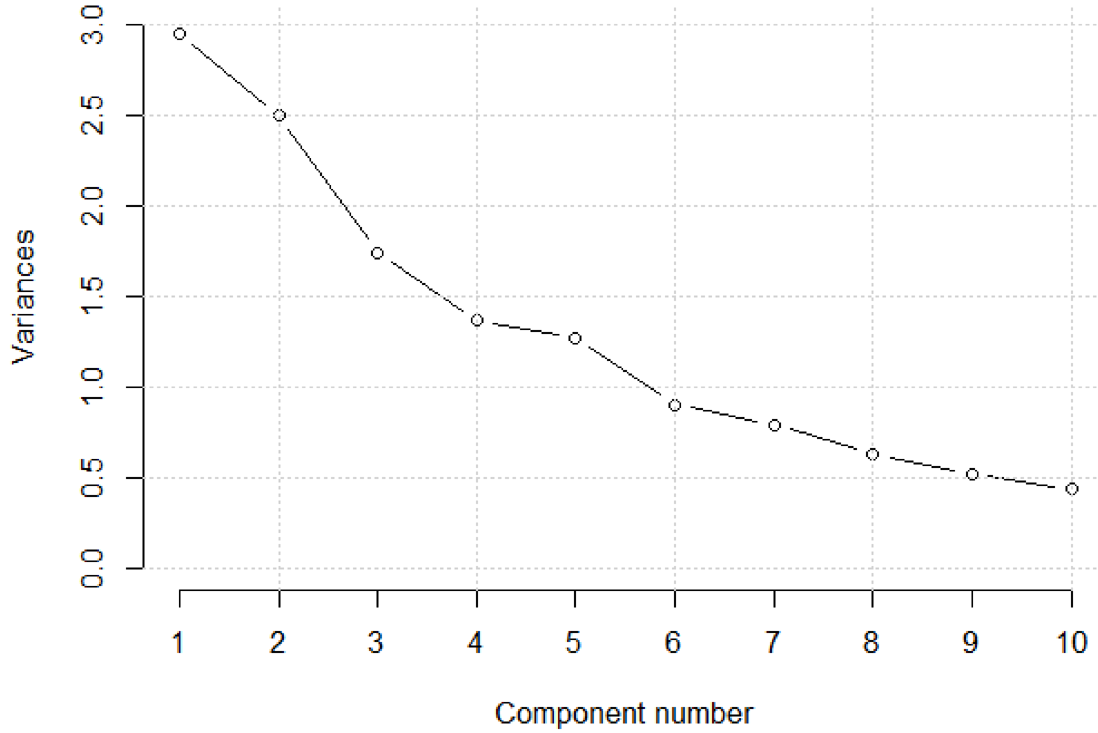


Figure E2: Scree plot from principal components analysis of socio-economic and environmental reservoir characteristics at small and medium-sized reservoirs in the Volta basin.

Table E2.1: Eigenvalues, proportional and cumulative variance of the correlation matrix in the principal components analysis

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Standard deviation	1.718	1.582	1.319	1.169	1.127	0.950	0.890	0.790	0.722	0.659	0.625	0.580	0.404	0.086
Proportion of variance	0.211	0.179	0.124	0.098	0.091	0.064	0.057	0.045	0.037	0.031	0.028	0.024	0.012	0.001
Cumulative Proportion	0.211	0.390	0.514	0.611	0.702	0.767	0.823	0.868	0.905	0.936	0.964	0.988	0.999	1.000

Table E2.2: Eigenvectors in the principal components analysis

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Reservoir dry months	-0.173	-0.367	0.265	0.310	0.123	0.127	-0.220	-0.192	0.287	-0.396	-0.441	-0.345	-0.002	0.010
Infant mortality	0.417	-0.198	0.112	-0.137	0.191	-0.167	0.213	-0.066	0.170	-0.279	-0.265	0.676	-0.089	0.005
Soil quality	0.098	-0.071	-0.087	0.133	-0.617	0.408	0.550	-0.087	-0.003	-0.303	0.077	-0.046	-0.044	-0.017
Labour	-0.424	0.124	-0.274	-0.189	0.182	0.221	0.237	0.051	0.084	-0.027	-0.316	0.168	0.647	0.006
Reservoir volume	0.258	0.538	-0.085	-0.027	-0.028	-0.020	-0.122	-0.024	0.126	-0.206	-0.199	-0.142	0.004	-0.708
Reservoir peri-vol ratio	-0.246	-0.540	0.110	0.029	0.062	0.033	0.116	0.021	-0.112	0.219	0.197	0.140	0.014	-0.705
Population density	-0.268	0.206	0.300	0.260	-0.351	-0.087	0.060	0.357	0.284	0.392	-0.367	0.243	-0.197	-0.003
Literacy	-0.421	0.120	-0.249	-0.236	0.295	0.135	0.209	-0.026	-0.001	-0.143	-0.079	-0.014	-0.717	-0.011
Runoff	0.243	0.156	0.302	0.021	0.347	0.444	0.262	-0.363	0.269	0.466	0.064	-0.107	-0.010	0.027
Access to roads	0.009	0.075	-0.176	0.565	0.350	-0.316	0.391	0.262	0.268	-0.138	0.306	-0.109	0.066	0.003
Access to towns	0.109	-0.134	-0.475	0.165	-0.027	0.448	-0.459	0.160	0.408	0.065	0.178	0.267	-0.080	0.001
Water quality	-0.057	0.224	0.444	0.168	0.225	0.436	-0.124	0.378	-0.376	-0.318	0.177	0.217	0.026	0.010
Access to cities	0.310	-0.137	-0.330	0.325	0.152	0.133	0.087	0.158	-0.516	0.259	-0.496	-0.103	-0.085	-0.001
Cattle density	-0.247	0.225	-0.096	0.476	-0.052	-0.089	-0.131	-0.652	-0.232	-0.003	0.051	0.378	-0.005	-0.006

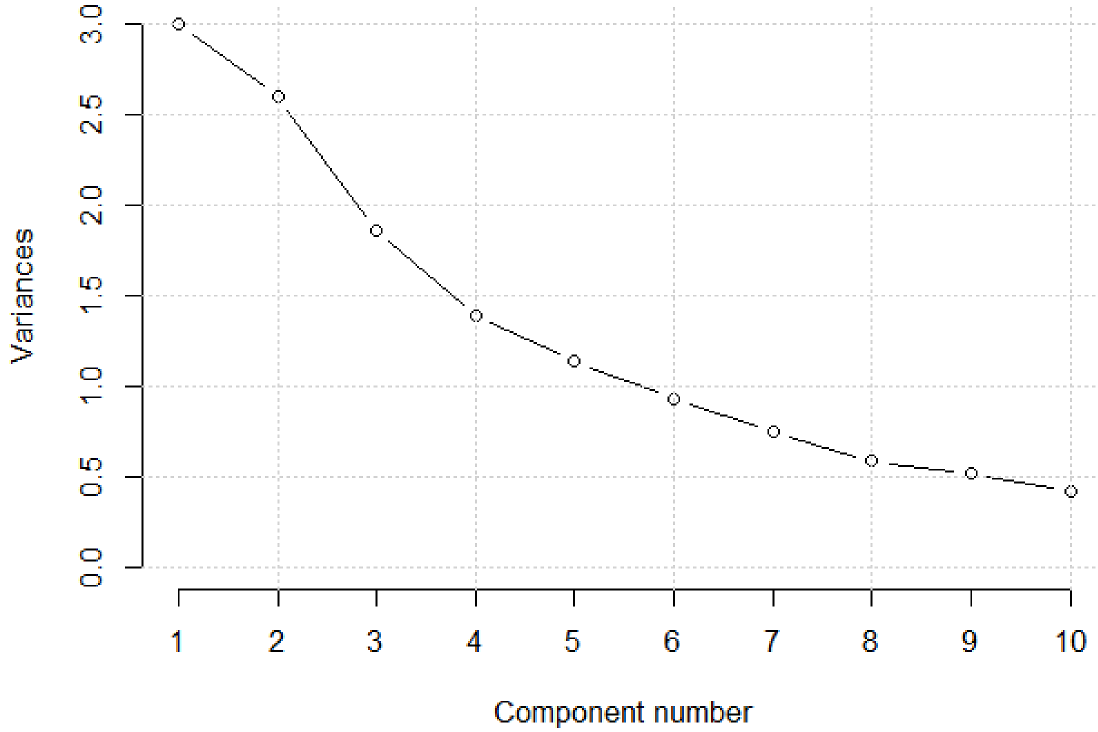


Figure E3: Scree plot from principal components analysis of socio-economic and environmental reservoir characteristics at small and medium-sized reservoirs included in the sustainability assessment.

Table E3.1

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Standard deviation	1.732	1.613	1.365	1.177	1.065	0.965	0.864	0.763	0.717	0.648	0.589	0.525	0.436	0.085
Proportion of Variance	0.214	0.186	0.133	0.099	0.081	0.067	0.053	0.042	0.037	0.030	0.025	0.020	0.014	0.001
Cumulative Proportion	0.214	0.400	0.533	0.632	0.713	0.780	0.833	0.875	0.911	0.941	0.966	0.986	0.999	1.000

Table E3.2

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Reservoir dry months	-0.105	0.427	-0.331	0.121	-0.118	0.055	0.162	-0.191	-0.319	0.106	-0.475	-0.513	-0.027	-0.015
Infant mortality	0.441	0.149	-0.011	-0.233	-0.114	-0.018	-0.213	-0.223	-0.304	0.168	-0.368	0.583	0.156	-0.004
Soil quality	0.005	0.074	0.083	0.322	0.694	0.267	-0.471	-0.164	-0.123	0.236	0.069	-0.075	0.014	0.015
Labour	-0.419	-0.051	0.293	-0.051	-0.178	0.334	-0.221	0.020	-0.040	-0.120	-0.335	0.184	-0.615	0.011
Reservoir volume	0.174	-0.562	0.100	0.087	-0.009	-0.069	0.066	-0.064	-0.160	0.085	-0.230	-0.198	-0.019	0.706
Reservoir peri-vol ratio	-0.157	0.564	-0.121	-0.103	-0.002	0.079	-0.044	0.054	0.136	-0.109	0.234	0.185	0.025	0.707
Population density	-0.315	-0.155	-0.362	0.163	0.187	-0.249	-0.245	0.322	-0.032	-0.440	-0.369	0.196	0.298	0.003
Literacy	-0.396	-0.077	0.292	-0.153	-0.302	0.299	-0.187	-0.041	-0.017	0.203	-0.011	-0.123	0.674	0.005
Runoff	0.299	-0.150	-0.271	-0.062	-0.108	0.576	-0.109	-0.273	0.024	-0.586	0.122	-0.125	0.068	-0.025
Access to roads	0.107	0.033	-0.069	0.494	-0.544	-0.198	-0.488	0.090	-0.220	0.036	0.309	-0.054	-0.099	0.005
Access to towns	0.052	0.155	0.441	0.390	0.062	0.151	0.435	0.181	-0.474	-0.313	0.057	0.168	0.153	-0.009
Water quality	-0.052	-0.193	-0.486	0.065	-0.042	0.460	0.214	0.427	-0.167	0.424	0.118	0.232	-0.054	-0.003
Access to cities	0.329	0.147	0.143	0.405	-0.116	0.209	0.017	0.243	0.635	0.089	-0.385	-0.003	0.098	0.014
Cattle density	-0.305	-0.128	-0.168	0.435	-0.078	-0.043	0.266	-0.646	0.196	0.076	0.038	0.361	0.044	0.005

Appendix F

Table F1 shows where there were significant differences in socio-economic and environmental factors at reservoirs with irrigation and canals, irrigation and no canals, and no irrigation, based on results of an ANOVA test. Table F2 shows the results of the subsequent post-hoc Tukey test of significance for differences in factors across pairwise combinations of each group.

*Table F1: Statistical differences in means of socio-economic factors between reservoirs that have 'No irrigation', 'Irrigation and canals', or 'Irrigation and no canals', at reservoirs <10 Mm^3 (n=1116), tested with an analysis of variance (ANOVA). Significance to the 95% level is indicated by ** and to 99% by ***.*

Variable	Degrees of freedom	Sum of squares	Mean square	F value	P-value
Access to cities (minutes)	2	0.9	0.5	0.5	0.624
Access to roads (metres)	2	2.8	1.4	1.4	0.246
Access to towns (metres)	2	7.3	3.7	3.7	0.026**
Cattle density (cattle per km^2)	2	147.8	73.9	85.1	<0.001***
Infant mortality (%)	2	1.8	0.9	0.9	0.408
Labour (%)	2	24.1	12.1	12.3	<0.001***
Literacy (%)	2	9.2	4.6	4.6	0.010***
Population density (persons per km^2)	2	29.1	14.5	14.9	<0.001***
Reservoir dry months (% of year)	2	137.6	68.8	78.3	<0.001***
Reservoir peri-vol ratio (m per m^3)	2	414.0	207.0	328.6	<0.001***
Reservoir volume (m^3)	2	422.2	211.1	339.1	<0.001***
Runoff (m^3)	2	43.8	21.9	22.8	<0.001***
Soil quality (% SOC)	2	0.5	0.3	0.3	0.777
Water quality (% contaminated)	2	41.8	20.9	21.7	<0.001***

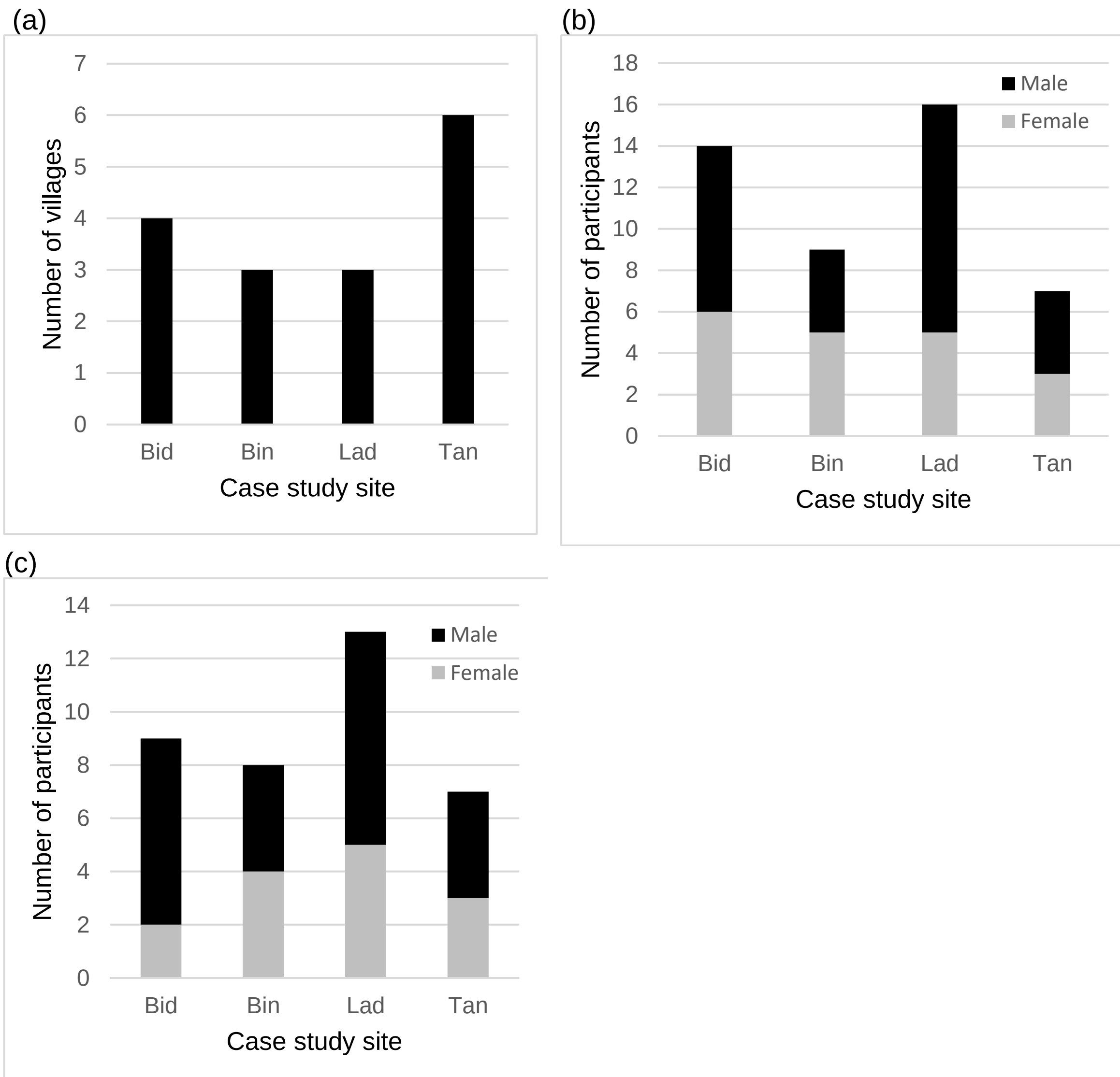
*Table F2: Statistical differences in means of normalised socio-economic factors between reservoirs <10 Mm3 (n=1116) that have 'No irrigation', 'Irrigation and canals', or 'Irrigation and no canals', tested with post hoc Tukey HSD. The table shows results for variables for which significant differences were identified in the ANOVA. Significance to the 95% level is indicated by ** and to 99% by ***.*

Variable	Groups	Difference (in Z scores)	Adjusted p-value	Mean +/- SD (Irrigation: No canals group)	Mean +/- SD (Irrigation: Canals group)	Mean +/- SD (No irrigation group)
Access to towns (metres)	Irrigation: No canals-Irrigation: Canals	-0.140	0.319	18391.2 +/- 13671.5	19537.9 +/- 12332.8	20422.3 +/- 14392.9
	No irrigation-Irrigation: Canals	0.037	0.915			
	No irrigation-Irrigation: No canals	0.177	0.020			
Cattle density (cattle per km2)	Irrigation: No canals-Irrigation: Canals	-0.103	0.488	24.1 +/-16.4	24.6 +/-13.7	14.3 +/-10.3
	No irrigation-Irrigation: Canals	-0.801	<0.001			
	No irrigation-Irrigation: No canals	-0.697	<0.001			
Labour (%)	Irrigation: No canals-Irrigation: Canals	0.003	0.999	54.9 +/-4	54.9 +/-3.5	56.1 +/-4.2
	No irrigation-Irrigation: Canals	0.297	0.003			
	No irrigation-Irrigation: No canals	0.294	<0.001			
Literacy (%)	Irrigation: No canals-Irrigation: Canals	0.066	0.775	36.6 +/-19	34.7 +/-16.1	39.5 +/-19.1
	No irrigation-Irrigation: Canals	0.225	0.038			
	No irrigation-Irrigation: No canals	0.159	0.042			
Population density (persons per km^2)	Irrigation: No canals-Irrigation: Canals	0.099	0.554	106.9 +/- 60.5	101.6 +/-58.6	92.5 +/-66.5
	No irrigation-Irrigation: Canals	-0.246	0.019			
	No irrigation-Irrigation: No canals	-0.346	<0.001			

Variable	Groups	Difference (in Z scores)	Adjusted p-value	Mean +/- SD (Irrigation: No canals group)	Mean +/- SD (Irrigation: Canals group)	Mean +/- SD (No irrigation group)
Reservoir dry months (% of year)	Irrigation: No canals-Irrigation: Canals	0.390	<0.001	23.4 +/-19.8	15.1 +/-11.2	35.1 +/-21.6
	No irrigation-Irrigation: Canals	0.941	<0.001			
	No irrigation-Irrigation: No canals	0.551	<0.001			
Reservoir peri-vol ratio (m per m^3)	Irrigation: No canals-Irrigation: Canals	0.646	<0.001	0.11 +/- 0.23	0.02 +/- 0.07	0.31 +/-0.32
	No irrigation-Irrigation: Canals	1.617	<0.001			
	No irrigation-Irrigation: No canals	0.971	<0.001			
Reservoir volume (m^3)	Irrigation: No canals-Irrigation: Canals	-0.652	<0.001	410152 +/- 1058930	1078062 +/- 1563449	35544 +/- 155030
	No irrigation-Irrigation: Canals	-1.633	<0.001			
	No irrigation-Irrigation: No canals	-0.981	<0.001			
Runoff (m^3)	Irrigation: No canals-Irrigation: Canals	-0.174	0.159	19356513 +/- 61969706	14640081 +/- 20470414	13259940 +/- 111513423
	No irrigation-Irrigation: Canals	-0.507	<0.001			
	No irrigation-Irrigation: No canals	-0.333	<0.001			
Water quality (% contaminated)	Irrigation: No canals-Irrigation: Canals	0.005	0.999	11.6 +/-7.6	11.8 +/-8.8	8.9 +/-6.1
	No irrigation-Irrigation: Canals	-0.385	<0.001			
	No irrigation-Irrigation: No canals	-0.389	<0.001			

Appendix G

Figure G1: (a) Number of villages represented in the focus groups, interviews and questionnaire surveys; (b) focus group participants by case study site and gender (n=46), and (c) questionnaire and interview survey participants per case study site and gender (n=37).



We used Chi-squared tests to check for significant associations between pairs of socio-economic factors used in the statistical analysis, and Goodman and Kruskal lambda to check for the strength of association (Figure S1.2). Most pairs of variables were not significantly associated, and those that were had a weak association (Lambda <0.45). Figure S1.3 shows contingency tables for those variables that were significantly associated.

Figure G2: Heatmap of associations between distinct categorical socio-economic variables used in the statistical analysis in this paper. The numbers in the grid cells are Lambda values, which show the strength of association between pairs of variables on a scale of 0 (no association) to 1 (perfect association). The Chi-squared P value is used to highlight, in red, cells where associations were significant to the 90% level (p < 0.1).

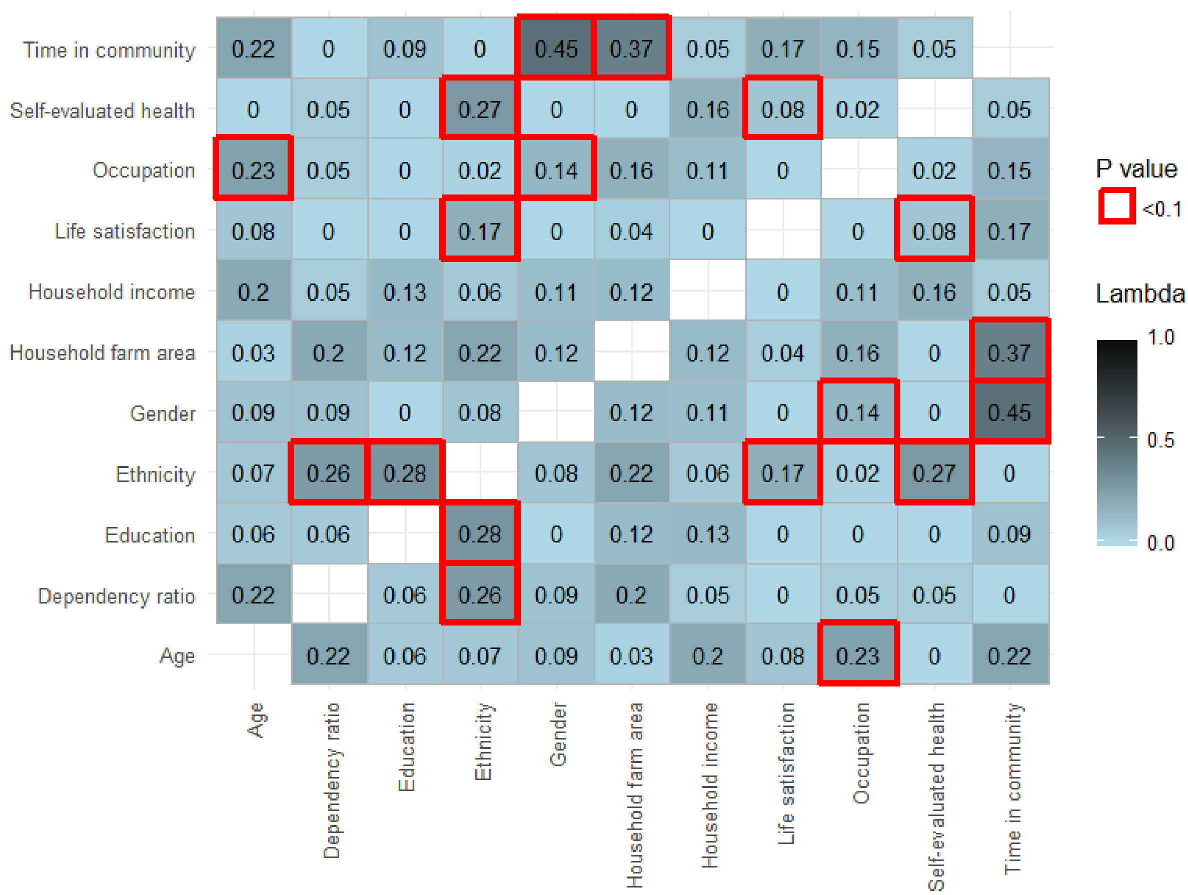


Table G3: Contingency tables for significantly associated socio-economic factors. Tables show (a) Time in community by Gender, (b) Time in community by household farm area, (c) Self-evaluated health by Ethnicity, (d) Self-evaluated health by Life satisfaction, (e) Occupation by Age, (f) Occupation by Gender, (g) Life satisfaction by Ethnicity, (h) Ethnicity by Household dependency ratio, and (i) Ethnicity by Education.

(a)		**Time in community (years)**	
		<34	**≥34**
Gender	**Female**	12	3
	Male	6	16

(b)

		Time in community (years)	
		<34	≥34
Household farm area (ha)	**<6**	12	5
	≥6	6	14

(c)

		Self-evaluated health (number of times too unwell to work in the last year)		
		Never	1 time	2 or more times
Ethnicity	**Bissa**	6	4	0
	Kusasi	8	2	3
	Mossi	0	7	1
	Minority	3	1	2

(d)

		Self-evaluated health (number of times too unwell to work in the last year)		
		Never	1 time	2 or more times
Life satisfaction	**Not satisfied**	2	3	3
	Satisfied	14	9	2

(e)

		Occupation		
		Rainfed crop farmer and/or business activity	Rainfed and irrigated crop farmer	Rainfed crop and livestock or fish farmer
Age (years)	**<45**	6	10	2
	≥45	4	6	9

(f)

		Occupation		
		Rainfed crop farmer and/or business activity	Rainfed and irrigated crop farmer	Rainfed crop and livestock or fish farmer
Gender	**Female**	5	9	1
	Male	5	7	10

(g)

		Life satisfaction	
		Not satisfied	Satisfied
Ethnicity	Bissa	1	9
	Kusasi	1	10
	Mossi	2	4
	Minority	4	2

(h)

		Ethnicity			
		Bissa	Kusasi	Mossi	Minority
Dependency ratio	<2.5	2	9	5	2
	≥2.5	8	4	3	4

(i)

		Ethnicity			
		Bissa	Kusasi	Mossi	Minority
Education	None	3	11	3	5
	Primary or above	7	2	5	1

Appendix H

Questionnaire used to collect information on participant socio-economic profiles in the Ghanaian study sites. An equivalent French version was used in the Burkinabé sites.

First name		Last name	
Community where you live		Length of time living in that community	
Age		Gender	☐ Male ☐ Female
Religious affiliation	☐ Christian ☐ Muslim ☐ None ☐ Other (please state):		
Ethnicity			
Level of education	☐ No education or preschool only ☐ Primary ☐ Secondary ☐ Higher		
Main occupation			
Other occupations			
Number of months spent away from community in a typical year			
Mobile phone owner	☐ Yes ☐ No	Electricity at home	☐ Yes ☐ No
Toilet facility	☐ Flush toilet ☐ Pit latrine ☐ Bucket		
Own livestock	☐ Yes ☐ No		
Regular source of income	☐ Yes Source: ☐ No		
Monthly income	☐ Less than 150 GHC per month ☐ 150 GHC to 350 GHC per month ☐ 350 GHC to 700 GHC per month ☐ More than 700 GHC per month		
Household monthly income	☐ Less than 150 GHC per month ☐ 150 GHC to 350 GHC per month ☐ 350 GHC to 700 GHC per month ☐ More than 700 GHC per month		

Household size (number of people living in household)			
Number of adults supporting household (including adults living outside)		Number of dependents	
Hectares of agricultural land owned / available (ha)		Hectares of this agricultural land farmed (ha)	
Hectares of agricultural land owned / available to the household (ha)		Hectares of agricultural land farmed by the household (ha)	
Time to get from household to farthest farmed field			
Main drinking water source		Time needed to get to the main drinking water source	
Use of water for irrigation	☐ Yes ☐ No		
Main irrigation water source		Means of transporting water for irrigation	
Distance between house and main irrigation water source		Distance between house and dam (if not main water source)	
How do you rate your own state of health?	☐ Good ☐ Moderate ☐ Poor	How many times have you been unwell in the last year?	☐ Never ☐ 1 time ☐ 2 times ☐ 3 or more times
How many times have you been too unwell to work in the last year?	☐ Never ☐ 1 time ☐ 2 times ☐ 3 or more times	Overall, how satisfied are you with your life?	☐ Very satisfied ☐ Satisfied ☐ Unsatisfied ☐ Very unsatisfied

Appendix I

Table I1 indicates the profile of individual farmers associated with quote IDs used in Chapter 5.

Table I1: Farmer case study affiliation, gender and age corresponding to quote IDs.

Quote ID	Site	Participant age	Participant gender
Bid1	Bidiga	30	Female
Bid2	Bidiga	20	Female
Bid3	Bidiga	35	Male
Bid4	Bidiga	23	Male
Bid5	Bidiga	24	Male
Bid6	Bidiga	53	Male
Bid7	Bidiga	40	Male
Bid8	Bidiga	20	Male
Bid9	Bidiga	42	Male
Bin1	Binaba	47	Male
Bin2	Binaba	43	Male
Bin3	Binaba	34	Male
Bin4	Binaba	45	Male
Bin5	Binaba	15	Female
Bin6	Binaba	20	Female
Bin7	Binaba	10	Female
Bin8	Binaba	50	Female
Lad1	Ladwenda	35	Male
Lad10	Ladwenda	51	Female
Lad11	Ladwenda	10	Male
Lad12	Ladwenda	22	Female
Lad13	Ladwenda	20	Female
Lad2	Ladwenda	30	Female
Lad3	Ladwenda	40	Female
Lad4	Ladwenda	21	Male
Lad5	Ladwenda	43	Male
Lad6	Ladwenda	47	Male
Lad7	Ladwenda	60	Male
Lad8	Ladwenda	30	Male
Lad9	Ladwenda	30	Male
Tan1	Tanga	30	Female
Tan2	Tanga	29	Female
Tan3	Tanga	70	Male
Tan4	Tanga	43	Male
Tan5	Tanga	67	Male

Quote ID	Site	Participant age	Participant gender
Tan6	Tanga	56	Male
Tan7	Tanga	20	Female

Appendix K

Table K1: Statistical differences in participant importance ratings for single ecosystem services, when participants are grouped by socio-economic factors. ***Only significant results are reported****, with significance to the 95% level indicated by *.*

ES	Factor	Groups	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Food – Plants	Household income	2-Low – 3-Moderate	-1.991	0.046*	5 – 5
	Self-evaluated health (number of times too unwell to work in last year)	2 or more times - Never	-2.025	0.043*	5 – 5
Food – Fish	Household dependency ratio	<2.5 - ≥ 2.5	2.746	0.006*	4 – 3
Food - Meat	Household dependency ratio	<2.5 - ≥ 2.5	2.286	0.022*	4 – 3
Fodder	Household income	2-Low – 3-Moderate	-2.172	0.030*	3 – 4.5
Water - Agricultural	Age	< 45 yrs - ≥ 45 yrs old	2.998	0.003*	5 – 4
	Education	No education – Primary level or above	2.280	0.023*	5 – 4
Desirable Flooding	Time in community	< 34 yrs - ≥ 34 yrs	2.439	0.015*	4 – 3
	Gender	Female - Male	2.722	0.006*	4 – 3
	Household farm area	<6 ha - ≥ 6 ha	2.541	0.011*	4 – 3
	Household income	1-Very Low – 3-Moderate	1.961	0.049*	4 – 3
Soil Moisture Retention	Ethnicity	Majority – Minority	2.137	0.033*	4 – 2

Table K2: Statistical differences in participant importance ratings for single ecosystem disservices, when participants are grouped by socio-economic factors. ***Only significant results are reported****, with significance to the 95% level indicated by *.*

Factor	Groups	ED	Z-values	P-values (Two-sided)	Median Importance (Group 1 – Group 2)
Agricultural Pests	Time in community	< 34 yrs - ≥ 34 yrs	-2.569	0.010*	3.5 – 5
	Ethnicity	Majority – Minority	-2.514	0.012*	4 - 5
	Life satisfaction	Not satisfied - Satisfied	2.065	0.039*	5 – 4
Human Disease Vectors	Household farm area	<6 ha - ≥ 6 ha	2.028	0.043*	5 – 5