Socio-hydrological drivers of agricultural water use in small reservoirs

Andrew Ogilvie[a,b,*] Jeanne Riaux[a], Sylvain Massuel[a], Mark Mulligan[b], Gilles Belaud[a], Patrick Le Goulven[a], Roger Calvez[a]

[a]*G-EAU, AgroParisTech, Cirad, IRD, IRSTEA, Montpellier SupAgro, Univ Montpellier, Montpellier, France*
[b]*Department of Geography, King's College London, WC2R 2LS London, UK*

Abstract

Millions of small reservoirs built across semi-arid areas present a potential to support agricultural livelihoods of rural smallholders. The scale and geographical dispersion of these multiple lakes restrict the understanding of these coupled human-water systems and the identification of adequate strategies to support riparian farmers. This research developed a multi-scalar interdisciplinary approach to characterise the hydrological and wider drivers of agricultural water use around multiple small reservoirs in semi-arid central Tunisia. The combination of field surveys, quantitative questionnaires and qualitative, semi-structured interviews confirmed minimal withdrawals, but highlighted the diversification of practices, the rise in fruit farming and peripheral benefits generated here by the development of 56 lakes. 48% of lakes provide residual benefits for the occasional watering of on average 300 fruit trees and support to downstream wells exploited for irrigation. A further 13 lakes (23%) provide high levels of benefits (900 fruit trees each), albeit with low equity, supporting essentially established farmers. The analysis of surface water assessments every 8 days from Landsat 5-8 imagery over 1999-2014, provides unprecedented insights into the significant water scarcity and unreliability that impedes agricultural intensification on 86 % of small lakes. Limited storage capacities and prolonged droughts highlight the need for small reservoirs in this climatic context to retain a supplementary irrigation objective and not strive to support widespread intensification of irrigated practices. Many farmers lack the capabilities to increase their withdrawals and suffer physical and economic water access difficulties, mismanagement, compounded through limited and short-term government assistance. Individual successes resulted from farmers' economic resilience and means to secure alternate water supplies during dry spells.

Keywords: Socio-hydrology; Remote sensing; Small reservoirs; Water harvesting; Tunisia

* Corresponding author. Tel.: +33-4-67-16-64-74 ; Fax: +33-4-67-16-64-27.
E-mail address: andrew.ogilvie@ird.fr

1. Introduction

1.1. Agricultural water uses in small reservoirs

By harvesting scarce and unreliable rainfall for local inhabitants, small reservoirs have the potential to supplement water resources and extend the growing season of farmers within poor rural areas (Wisser et al., 2010). Their reduced costs and ability to be implemented at the scale of individual farms or clusters notably supports recent efforts to recognise and promote irrigation and water management practices of millions of smallholders (Vincent, 2003). Studies revealed multi use systems (Ayantunde et al., 2018; de Fraiture et al., 2014) with diverse benefits including watering livestock, irrigation, fish production as well as recreational and cultural importance. Agricultural production remained sometimes limited (Faulkner et al., 2008; Habi and Morsli, 2011; Khlifi et al., 2010; Mugabe et al., 2003) leading to concerns by donors and investors despite the strong demand and apparent affection for reservoirs by users (Venot and Hirvonen, 2013). This contradiction highlighted the difficulty in identifying and quantifying the real outputs of these systems, partly due to the inherently subjective and restrictive frameworks used, centred on issues of agricultural performance, efficiency or productivity (Venot and Krishnan, 2011).

Literature on the reasons which constrain, or favour agricultural water use in small reservoirs remains scarce. Hydrological limitations and user uncertainties over water availability have been highlighted (Mugabe et al., 2003), however other observations pointed to insufficient resources to cover investment & maintenance costs, lack of adequate management structures (Zairi et al., 2005) or the consequence of government strategies and siting criteria (Talineau et al., 1994). The overlapping interactions between drivers of agricultural water use remain poorly understood, often as a result of mono-disciplinary studies considering agronomic, social (i.e. cultural, economic, institutional) and hydrological factors separately.

1.2. Investigating socio-hydrosystems

The recent surge in scientific literature in socio-hydrology (Di Baldassarre et al., 2013; King et al., 2012; Montanari et al., 2013; Riaux, 2013; Sivakumar, 2012; Sivapalan et al., 2012) highlights the growing recognition of the importance and difficulties in studying the mutual interactions in human-water systems. Despite the popularity for the recently coined term, the concept refers to common contemporary approaches which recognise the importance of human interactions within hydrological systems (Falkenmark, 1977), as in other socio-ecological systems (Ostrom, 1990). This begun with considering human influences, such as withdrawals, impoundments and other human induced changes on hydrological systems, moving away from theoretically undisturbed natural systems (Thompson et al., 2013). Conversely, it also focussed on the influence of hydrological systems on human interests, notably water variability on water & food security and the consequences of flood dynamics (Di Baldassarre et al., 2013) and droughts. Socio-hydrology represents a step further to provide new insights on the broad, complex interactions and retroactions (Braden et al., 2009; Wesselink et al., 2017) of coupled human-water systems. Understanding the finer workings of these socio-hydrosystems notably requires in depth field investigations (Massuel et al., 2018), which must be transcribed into operational approaches, modus operandi (Hale et al., 2015; Sivapalan et al., 2012). Suitable approaches must notably seek to extract value from incorporating the approach and viewpoints of other disciplines, rather than simply combining their results. By exploring and borrowing different tools, such interdisciplinary approaches may address water and society issues from a different perspective, and allow new topics and new questions to be investigated and generated (Massuel et al., 2018; Riaux and Massuel, 2014). This field-based "comparative sociohydrology" may then identify key variables to account for when upscaling or transposing such investigations and according to Pande and Sivapalan (2016) may feed into wider socio-hydrological modelling research.

An original socio-hydrological approach is developed here to investigate the agricultural water uses around multiple small reservoirs and the drivers which foster or constrain agricultural development on their banks. Understanding the dynamics around small reservoirs requires a comprehensive framework to study the reservoir's hydrology, the riparian community and the way they are interlinked.

2. Methods

Research combined hydrological monitoring, numerical modelling, remote sensing, ethnographic enquiry and qualitative analysis while developing a nested scale approach, to provide varying depth of analysis, as we proceeded to upscale observations on individual small reservoirs to more than 50 small reservoirs scattered across a 1200 km^2 catchment in semi-arid Tunisia.

2.1. Case study site

The study site is the Merguellil upper catchment (1200 km², figure 12) situated in semi-arid central Tunisia (329 mm/year ± 131 mm), where 56 small reservoirs were built as a result of successive water and soil conservation programmes since the 1960s (Khlifi et al., 2010; Selmi et al., 2001). Following a nationwide strategy setting ambitious objectives of 1000 small reservoirs, 700 small reservoirs were built nationally by the late 1990s for an estimated capacity of 70 Mm^3. Around Kairouan, this 1st phase led to the construction of 39 small reservoirs, followed by a second phase after 2002, supported through a host of additional international projects (CNEA, 2006).

The 56 lakes were inventoried through the combination and cross referencing of records from local authorities, literature (CNEA, 2006; Kingumbi, 2006; Lacombe, 2007), satellite imagery and field visits (Ogilvie et al., 2016). The area has been the focus of numerous agricultural surveys, and a vast hydrological and climatic observation network (Albergel and Rejeb, 1997; Leduc et al., 2007), which included the monitoring of 13 small reservoirs, considering the importance of climatic and human changes on the downstream irrigated Kairouan plain. Initial design capacities of small reservoirs in the catchment range between 17,000 m^3 and 1,590,000 m^3 though the median size only reaches 66,000 m^3. Land uses in the catchment are dominated by traditional Mediterranean crops, mostly rainfed cereals (30% of catchment surface area) and fruit trees (20%), especially olive groves suited to the extended dry season. Grasslands cover 30%, forest 19% and towns and watercourses the remaining 1% (Dridi et al., 2001). 3 500 ha (fruit trees and market gardening) are irrigated, mostly from unregulated groundwater resources (Le Goulven et al., 2009).

2.2. Assessing water availability

Water resources were assessed across 48 lakes based on surface water assessments acquired from 546 Landsat 5-8 images over 1999-2014. The method described in Ogilvie et al. (2018) uses a fixed threshold Modified Normalised Difference Water Index (Xu, 2006) calibrated against extensive field data. Surface area are converted to volumes using a locally derived surface volume rating curve, where the B and β model parameters were incremented over time to account for silting, based on known maximum capacity and construction date (Ogilvie et al., 2016). Time series were spline interpolated and gap filled using the TSGF extension (Forkel et al., 2013) in order to allow water availability statistics to be calculated over time. RMSE on mean annual volumes reaches 20 600 m^3. Lakes built recently (Daoud 3 & Mdinia 2 in 2012) as well as 6 minor lakes (e.g. Bouksab 2) for which maximum capacity data was not available were excluded from the water availability analysis. To allow unbiased comparison of all lakes, interannual water availability was also assessed over the common period 2007-2014 when all 48 lakes were in operation.

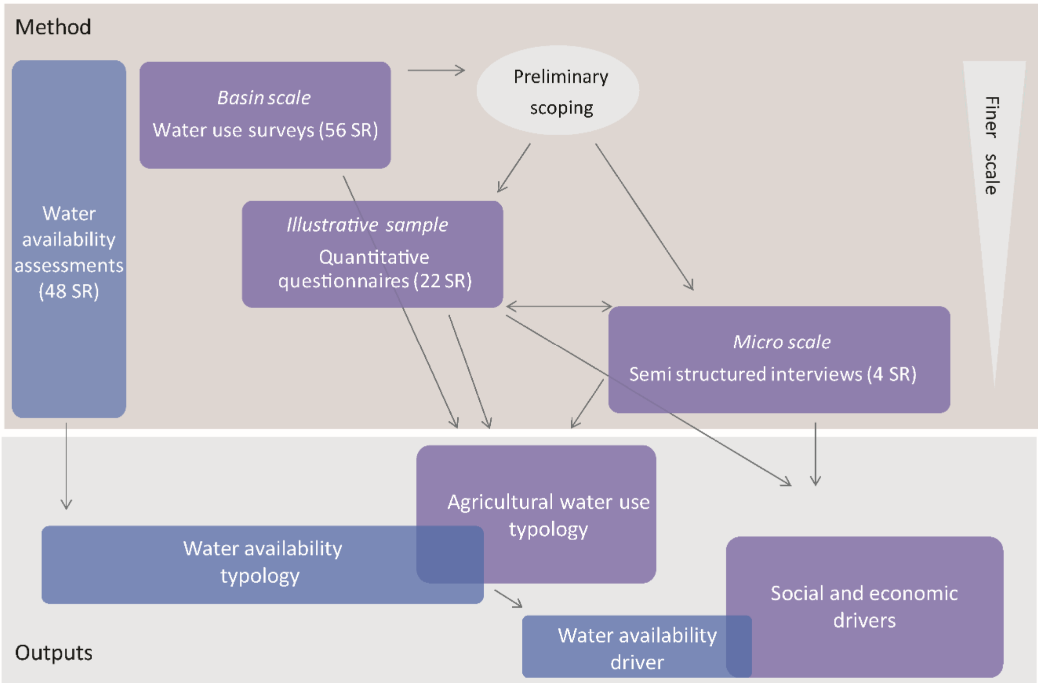

Figure 1: Schematic representation of methodology used to determine water uses and associated socio-hydrological drivers in multiple small reservoirs (SR)

2.2.1. Characterising agricultural water availability

Considering water uses depend on the amplitude but also the timing and duration of the flood, the number of days that water levels exceed a given volume were calculated for each lake to highlight the irrigation potential. Values were calculated over the whole year and the 6 months of dry season (April-October), when potential watering needs are greatest. A 5000 m^3 threshold was chosen based on interviews as it reflected sufficient water availability to promote irrigated activities by two farmers. These farmers developed market gardening or fruit trees, withdrawing water for 8 hours/day, 3 or more days/week. Significantly it also complies based on the height-surface-volume (HSV) rating curves with a minimal water depth of 1 m, required according to interviews by users to operate pumps without silt from the lake floor bed clogging the pumps. Aggregating a minimum of 6 Landsat pixels also reduced the presence of single outliers, whilst remaining inferior to the size of the smallest lakes (0.5 ha). The 48 lakes were then categorised based on the length of time they succeeded or failed to meet the required water threshold.

2.3. Characterisation of water uses

Water uses associated with small reservoirs were examined through a combination of field surveys, quantitative questionnaires as well as semi-structured interviews borrowed from ethnographic methodologies. A multi-stage sampling methodology (Mushtaq et al., 2007) was used to identify broad water use characteristics at the catchment scale, and define with greater detail water uses and profile water users on a selection of lakes (figure 1).

2.3.1. Water use field surveys on 56 lakes

Field surveys enabled preliminary scoping of the type of water uses across all 56 reservoirs. Surveys undertaken between April and June 2011, noted the presence and number of pumps, watering pipes (*bergater*) and cisterns which allow watering from the lake. They also qualitatively listed the presence of nearby habitations, fruit trees, market gardening, rainfed crops, grazing and watering livestock nearby. Flood recession cropping on the banks of the lake to benefit from increased and prolonged soil moisture was also recorded, as were nearby wells under the influence of lakes, considering their potential benefit for groundwater recharge (Selmi and Zekri, 1995). Furthermore, all water supply sources (spring, boreholes, wadi) were inventoried to highlight the role of these lakes in supplementary irrigation.

Information collected through these water use surveys on 56 reservoirs was compared with previous inventories undertaken in 1999 and 2005, at similar periods of the year (Lacombe, 2007). In 1999, interviews focussed on 43 reservoirs while in 2005 extensive agricultural use surveys were carried out on 25 lakes in the region. Additional local studies (Selmi et al., 2001; Selmi and Zekri, 1995) and reports including original project documents and evaluation reports (e.g. CNEA, 2006) were used, notably to identify the original objectives of lakes and the wider assistance provided to riparian farmers.

2.3.2. Agricultural questionnaires on 22 lakes

Preliminary scoping on all 56 lakes distinguished 24 lakes with motor pumps and 23 lakes without. A further 9 lakes potentially supported the recharge of nearby wells. The latter were differentiated considering the different dynamics, in terms of water resources, access, government support, involvement in water use association, prior irrigation experience, etc. (Selmi and Talineau, 1994) A sample of 22 reservoirs was then chosen to carry out quantitative questionnaires about agricultural practices and water uses. 16 lakes studied in 2005 were included to provide diachronic assessments of agricultural water uses and management. Additional lakes were randomly selected to investigate a total of 17 lakes (75%) equipped with motorpumps. 4 lakes with no apparent withdrawals were investigated to specifically explore the reasons behind these. One further lake supporting the recharge of nearby wells was included.

All 48 farmers on the 22 lakes were interviewed on the following topics: household and livelihood strategies, farm characteristics, agricultural practices across each plot (crop types, surface areas, yields, watering regimes, livestock), water access and water uses, lake withdrawals, water management, and future perspectives. Additional questions on land rights and government assistance to draw out potential constraints influencing water use were also included based upon the insights gained in the semi-structured interviews.

2.3.3. Semi-structured, in-depth interviews on 4 lakes

25 semi-structured, in-depth interviews were undertaken (over 2011-2013) with farmers on four reservoirs presenting a cross section of water use, availability and issues identified through initial surveys (Riaux et al., 2014). As a qualitative tool, semi-structured interviews were not intended to be multiplied for the sake of increasing representativity, and instead sought to illustrate and shed light on specific complex issues which other (faster) methods are unable to (Beaud, 1996; Longhurst, 2009). This technique, combined with observations and literature review to form an ethnographic framework, seeks to build greater trust with the interviewee and allow for more personal, confidential or sensitive information to be disclosed, relating here to conflicts or political and economic constraints. The open framework also allowed for a comprehensive assessment of wider, unsuspected uses, benefits and issues to be captured, in contrary to predetermined, constrained and subjective framework (Becker, 1998; Venot and Cecchi, 2011).

Discussions focussed around predetermined topics identified from the literature and initial visits to the reservoirs, which sought to paint a portrait of how lives had evolved around the reservoir after its construction, (life story, Denzin and Lincoln (1994)). Based only on the assumption that people exploit the available resources, this work followed the grounded theory approach (Glaser and Strauss, 1967) to understand the drivers which explain the apparent low agricultural water use (Lacombe, 2007; Riaux et al., 2014). Focusing on the history of the site, the origins of the small reservoir and its management and water uses, discussions sought to understand in greater detail the influence of water user associations, land and water rights, government incentives, economic difficulties and conflicts. High resolution Digital Globe and Astrium satellite imagery (available in Google Earth and Bing Maps) were used as a visual aid to represent the location of plots and pumps, and stimulate discussions (*carte parlée*, Collard and Burte (2014)). Interviews were not recorded, but transcribed and typed up collectively to iron out uncertainties or incoherences (Beaud, 1996).

2.4. Deducing socio-hydrological constraints to water use

The information extracted through quantitative agricultural interviews and qualitative semi-structured interviews were combined to characterise the users and their agricultural practices on 22 small reservoirs. Based on the information gathered through rapid surveys across all reservoirs, key water use characteristics of each lake and their statistical distribution were identified, leading to a typology of the 56 lakes' agricultural benefits. Withdrawal patterns including average pumping duration and frequencies during the dry and rainy seasons for each category of lakes were calculated from the questionnaire data (Ogilvie, 2015). Higher resolution in the withdrawals estimates was not relevant considering the high uncertainties observed in the number of pumps in operation each year and on each lake.

The water uses and water availability typologies were then crossed on the common subset of 48 lakes to identify where water availability is constraining or supporting agricultural water use. The incoherences highlighted, associated with the in-depth knowledge gained through ethnographic enquiry, then helped shed light on the multiple social (cultural, historical, political, institutional) and economic drivers which influence agricultural development around small reservoirs. Interpretation of the dynamics around reservoirs followed an iterative process, whereby initial hypotheses deduced from observations were gradually confirmed or invalidated through the interviews and hydrological assessments. Interviews trigger new questions and hypotheses which progressively reorient, refine and nuance our evolving understanding of this socio-hydrological system. The multiple replies obtained allow us to triangulate the information (e.g. who shares the pumps, did the government assist, what happened to the water user associations, conflicts, etc.) until we reach a saturation point where the additional information only reinforces the confidence in our interpretation of the system but ceases to provide new insights (Olivier de Sardan, 2005). Feeding the insights gained from interviews into the design of the questionnaires (e.g. questions on land rights, water user associations) allowed us to identify the spatial, statistical distribution of these drivers and help upscale local observations.

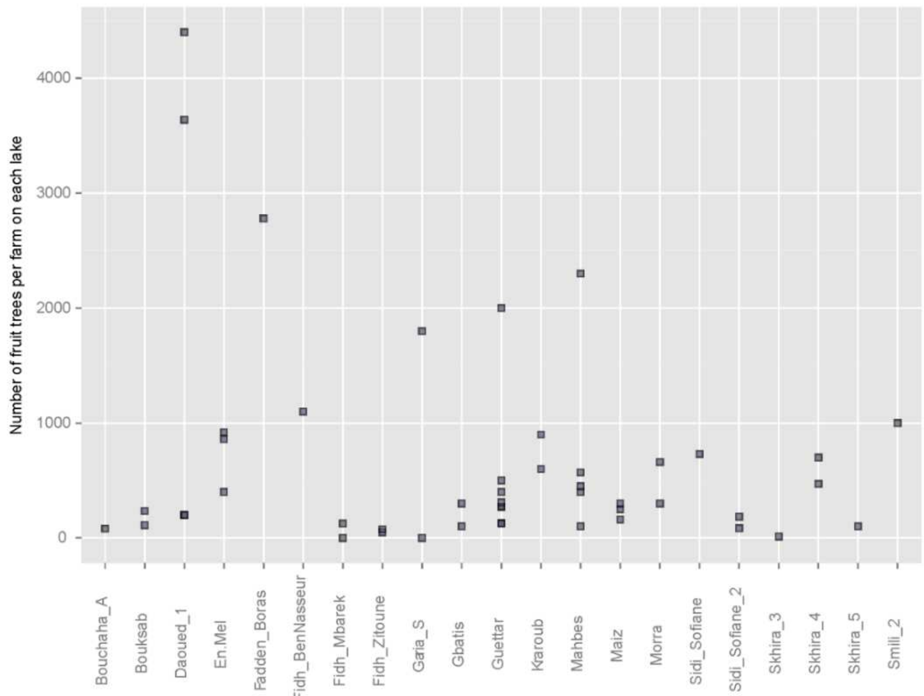

Figure 2: Observed heterogeneity in the number of fruit trees per farm and per lake based on questionnaires

3. Results and discussion

3.1. Supporting and diversifying livelihoods around small reservoirs

The introduction of small reservoirs was first and foremost accompanied by a change in agro-pastoral activities, notably the development and expansion of irrigated practices, sometimes at the expense of other livelihood strategies.

3.1.1. Fruit tree farming

Fruit trees were observed on the banks of over 80% of all lakes. These were cultivated by all interviewed farmers, 58% of which declared taking up arboriculture activities following the construction of the lake. The number of fruit trees ranged from 4400 over 20 ha to 13 trees on 0.5 ha (mean = 720 trees on 6.3 ha) highlighting the variability across farms and lakes (figure 2). Only a few farmers strive to expand the number of trees on their land (El Maiz, Sidi Sofiane 2, Mahbes, Morra), with most others having already exploited all their land and only planting new trees to replace dead ones. Olive trees dominate (61.2% of fruit trees) and yield around 1-2 *galba*/tree (1 *galba* is equivalent to 1 litre of oil or 14 kg), providing for the family consumption and additional revenue during good years for 65% of people surveyed. Values are consistent with Selmi et al. (2001) (mean 8 ha on 57 lakes in the wider Kairouan governorate) but significantly lower than those in CNEA (2006) (2000-3000 fruit trees on 20 ha), partly due to the greater proportion of lakes with large exploitations in their sample. In Jendouba, northern Tunisia, Khlifi et al. (2010) reported an increase in the average surface area for trees from 3 ha to 23 ha over 8 years following the introduction of small reservoirs, however this region benefits from comparatively higher rainfall (450-950 mm from South to North), not accounting for additional socio-economic differences which may explain this dynamic.

Farmers rely on motor driven pumps to draw water from the lake which is conveyed to the plots using bergater pipes and a network of trenches and impoundments to channel water to each tree. Some farmers had built a basin and practised gravity-fed irrigation (Mahbes, Daoued) while drip irrigation was only recorded on three exploitations (Sidi Sofiane, Fadden Boras and El Kraroub). The filling of cisterns was only allowed on 45% of lakes surveyed and on half of these, their use was restricted to riparian farmers, which reached as many as 20 families (Garia S, Skhira 3, O. El Haffar or El Mahbes). On the other half, cisterns were also provided to farmers from further afield for supplementary irrigation, for free (50 cisterns/year at Morra, 100 at Skhira 4) or sold as on O. Daoued 3 where 4 cisterns of 3000 l at a time operate, and up to 50 cisterns per day are withdrawn during summer months.

3.1.2. Market gardening

Market gardening had been attempted at some stage on 80% of lakes surveyed and by 65% of farmers interviewed but only 20% of these continue this activity today (figure 3). Surface areas were typically small (under 0.5 ha) and mostly for personal consumption except for two farmers surveyed for whom market gardening became and remains today an income generating activity (Ain Smili, Guettar). These values are close to those observed by (Selmi et al., 2001) who had previously observed an average of 0.25 ha for market gardening on lakes in the region, and similarly observed a rapid decline of activity within three years.

3.1.3. Cereals

In very rare instances (Morra and Sidi Sofiane), farmers had installed sprinklers (up to 9 over 3 ha) to exploit water from the lake during the early phases of cereal growth. In both cases, the practice ceased rapidly as unreliable rainfall during the rest of the growth period during which they chose not to continue watering reduced all benefit. Similar practices in the Jendouba region had also been observed on a handful (3 out of 18) of reservoirs but again only over the first two years (Khlifi et al., 2010). Cereal cropping continues to be practised by 70% of farmers around small reservoirs, but 20% declared ceasing rainfed cereals after the lake's construction to concentrate on fruit trees. This conversion remains much less significant than around small reservoirs around Jendouba where in 2 years, people reportedly all converted to fruit farming and market gardening (Khlifi et al., 2010). In certain cases (Skhira), soil humidity on the contours of lake were used to advantage by farmers to grow cereals (flood recession cropping), however benefits can be outweighed by potential flooding and several farmers preferred to refrain from cropping near the reservoirs to reduce risk of damage to their crops.

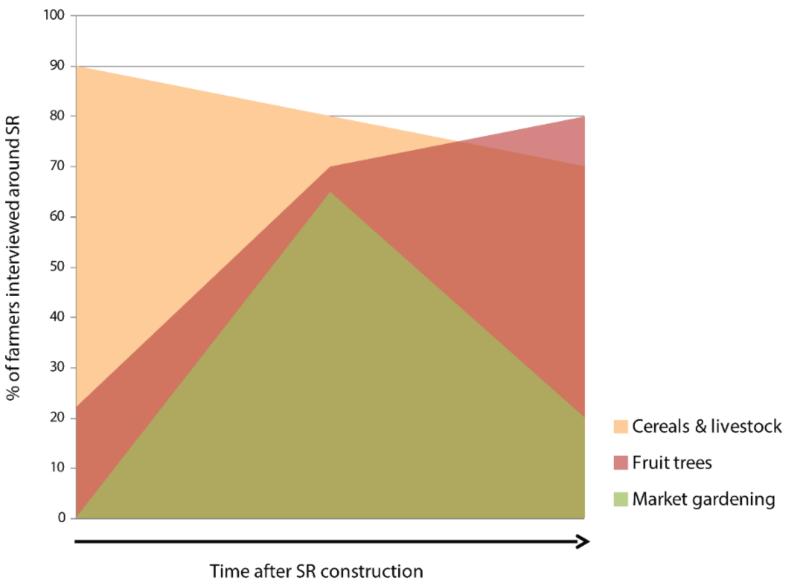

Figure 3: Diversification of agro-pastoral practices following the small reservoir construction based on farmer interviews (N.B. indicative timespan 20 years)

3.1.4. Livestock

Livestock is a major traditional activity and 70% of lakes surveyed were reportedly used to water livestock. In certain remote areas with limited alternate water supply, lakes reduce the distance livestock must travel, thereby increasing productivity of the herd. 27% of farmers declared abandoning this activity following the construction of the lake, as farmers reported having less time to water and feed their stock, but also due to increasing pressure on land leading certain years to conflicts over fodder, as well as increased theft since the 2011 revolution.

3.1.5. Groundwater recharge and peripheral water use

Farmers on 12 lakes witnessed the positive influence of the lake on the level and recovery times of their wells, which support fruit tree and market gardening activities. This positive effect was notably documented (Selmi and Talineau, 1994; Selmi and Zekri, 1995) on two wells downstream of Gouazine where groundwater levels rose by 11 m and 4 m respectively after the dam was built, as well as in other parts of Tunisia (Zairi et al., 2005). Geochemical studies in the region (Gay, 2004; Montoroi et al., 2002) showed that infiltration reached 300 m^3/day on the Gouazine lake, and that this signal was observed on wells exploiting shallow aquifers 350 m downstream within 100 days (figure 4). Eight reservoirs were specifically designed to favour recharge (cf. table A1) of the local (Bou Hafna, Cherichira) aquifers (CNEA, 2006).

Figure 4: Irrigated agriculture on wells situated directly downstream from the Gouazine lake

3.1.6. Protecting downstream areas

Reservoirs as part of the national water and soil conservation strategy were also designed to contain silt and reduce silting of downstream areas and lakes. Based on mean sedimentation rates across 14 reservoirs in the region, over 200 000 m^3 sediment may be collected annually by reservoirs in the catchment (CNEA, 2006; Ogilvie, 2015). This corresponds to a reduction of the order of 15% of silting in the downstream El Haouareb dam, estimated around 1.33 to 1.48 Mm^3/year. Other lakes were also designed to protect roads (Bouksab 2 & 3) or plots (Fidh Ben Nasseur) situated directly downstream from floods.

Reducing available capacities over time, the captured silt causes discontent from farmers and problems were also reported due to the detrimental flushing of accumulated silt and debris onto the land of farmers situated below (Bouchaha, Fidh Ben Nasseur).

3.1.7. Other social and economic benefits

People interviewed also mentioned the wider value of lakes, including the contribution to landscape, shaded ecosystems, recreational benefits (swimming), duck populations attracting hunters, bee keepers placing their hives (Guettar, Mahbes), water for house construction and washing wool (Morra, Guettar). Household use was only mentioned on 8 out of 22 lakes surveyed, as public fountains are relatively widespread, though can be used during common water shortages. Biodiversity benefits have yet to be investigated. Farmers notably expressed attachment to their lakes, which were also for some a source of prestige (e.g. Ain Smili).

Significantly, in addition to being a material resource capable of increasing local production, lakes appeared as an immaterial resource that plays a key role in structuring and maintaining local social groups (Riaux et al., 2014).

3.2. Typology of lakes' agricultural benefits

Based upon the qualification of water uses across 22 lakes and the rapid surveys carried out across the 56 lakes, the benefits of lakes from the farmers' perspective were characterised into three categories (tables 1 and A.1).

Table 1: Categorisation of 56 small reservoirs based on agricultural water uses

Lake Category	Negligible benefits	Residual benefits	Isolated, high benefits
Number of lakes	16	27	13
Initial capacity			
Min	17,000	18,000	40,000
Mean	181,000	1,200,000	1,590,000
Max	65,000	166,000	490,000
Mean annual availability (m^3/day, 2007-2014)			
Min	340	900	5,200
Mean	16,900	230,000	302,000
Max	7,200	29,300	80,800
Mean number of pumps	0	1.1	2.5
Fruits trees/farm	N/A	300	900
Market gardening/farm	N/A	Up to 0.5 ha	Up to 2.5 ha
Withdrawals (m^3/month/lake)	0	Up to 1200	Up to 4100

3.2.1. Lakes with negligible benefits to users

These (16) lakes currently support negligible agricultural withdrawals, and do not visibly recharge any nearby wells. These include (9) lakes which never did support agriculture and have essentially a protective value, reducing erosion and flooding of downstream areas. In certain cases, this corresponds to their primary objective (table A.1) but a few larger lakes failed to develop irrigated practices, largely due to their isolated location (Chaouba El Hamra and Marrouki 2). Other lakes ceased to support agriculture after becoming completely silted (Ben Houria, Bouchaha B) or sufficiently to be abandoned (Skhira A) or now only allow for the occasional watering of a few trees, up to 100.

3.2.2. Lakes with residual benefits to users

These (27) lakes support occasional withdrawals, and provide small, irregular but noticeable benefits to nearby farmers. These support agriculture directly through motor pumps (13) or through cisterns (8) while a total of 10 (also) support water levels of nearby wells exploited for irrigation. The number of pumps remains low (1 per lake on average) and withdrawals essentially support the occasional watering of fruit trees. Sampled exploitations possess on average 300 (up to 1000) fruit trees, 7 ha of cereals, between 10 and 50 heads of sheep, and when availability is greater, occasional small-scale market gardening (0.5 ha) for domestic consumption continues to be observed. This largest category includes lakes of all sizes, including very small lakes (under 40,000 m^3 capacity) where single riparian farmers continue to occasionally pump on the lake, to large lakes (over 800,000 m^3 capacity) where the low number of pumps installed (2-3) reflect the low exploitation of these lakes. Several of these lakes were built to support irrigation, while others (Skhira 4&5) built in the 1960s to protect from soil erosion, have supported the development of several orchards through direct pumping and nearby wells.

3.2.3. Lakes with isolated, high benefits

These (13) lakes support modest regular withdrawals and have assisted the development of isolated but significant exploitations. Two of these are currently exploited using only cisterns while the others withdraw using motor pumps (2.5 pumps per lake on average), and two lakes also contribute to recharging nearby wells. Activities focus essentially around fruit trees which reached 900 on average across our sample (and up to 4400), 15 ha of cereals and between 10 and 50 heads of livestock essentially sheep. Commercial market gardening of 2-5 ha was attempted but farmers preferred to focus on fruit trees, even using drip irrigation on three lakes. Lakes were often large (table A.1) but also include two smaller lakes (40,000 m^3). In most cases though, the benefits are the results of individual entrepreneurs and the lakes and pumps appear to have contributed in reinforcing existing capabilities. These lakes suffer from low equity, where benefits are confined to single users, who possessed existing capital or reliable sources of income (e.g. Fadden Boras).

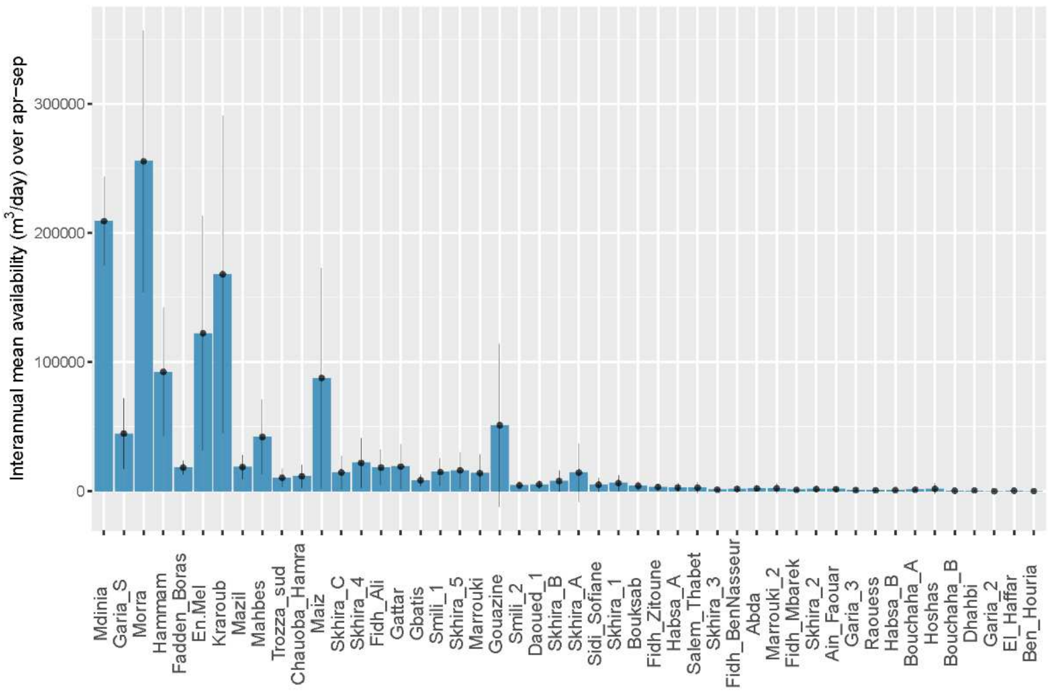

Figure 5: Mean interannual availability over 2007-2014 per lake over the dry season displayed as mean ±1 standard deviation

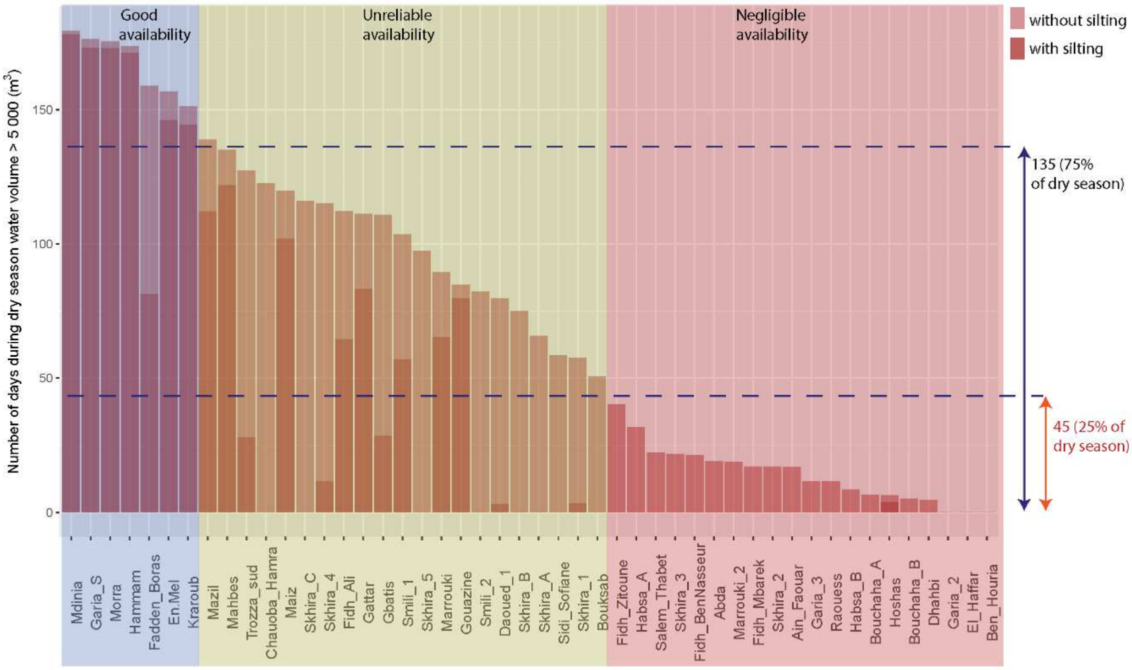

Figure 6: Definition of water availability categories based on mean number of days during 6 dry months where water availability exceeded 5000 m^3 over 2007-2014

3.3. Agricultural water availability characterisation

Analysis from Landsat observations in Ogilvie et al. (2016) highlighted the high variability of mean water availability across 48 small reservoirs, ranging from 100 m^3/day to 255,000 m^3/day on larger lakes (mean = 28,000 m^3/day) over the 6 months of the dry season. Interannual variations were high on the smallest lakes (variation coefficient > 2) but remarkably the variation coefficient also reached 0.75 on large lakes over 1 Mm^3 capacity such as Kraroub and En Mel. By considering the number of days water volumes exceed 5000 m^3, three classes of lakes were here distinguished, according to their capacity to support agricultural intensification.

3.3.1. Negligible water availability

The first category consists of lakes with negligible water potential. A minimum of 45 days during the dry season where water resources exceeded 5000 m^3/month was considered necessary to support market gardening activities based on minimal crop cycles lengths. When accounting for silting, 27 lakes never reached the required water availability and a further 6 met this requirement for less than 45 days during the 6 dry months (i.e. below 25% of dry season days). For 20 of these, figure 6 confirmed that uncertainties over silting rates were not significant as even under the best case scenario of maintaining initial capacity through dredging or building new dams at these locations and dimensions, these continued to fail to meet the defined availability requirements. On the other 13 lakes, sensitivity to the silting model was much greater (e.g. Chaouba El Hamra, figure 6) and as field visits confirmed (minimal) storage capacity and occasional pumping, these 13 lakes were therefore classed in the unreliable availability category. These confirm the difficulties of modelling over space and more than 30 years discrete silting phenomena (Ogilvie et al., 2016), influenced by topography, lithology, rainfall regimes and land uses.

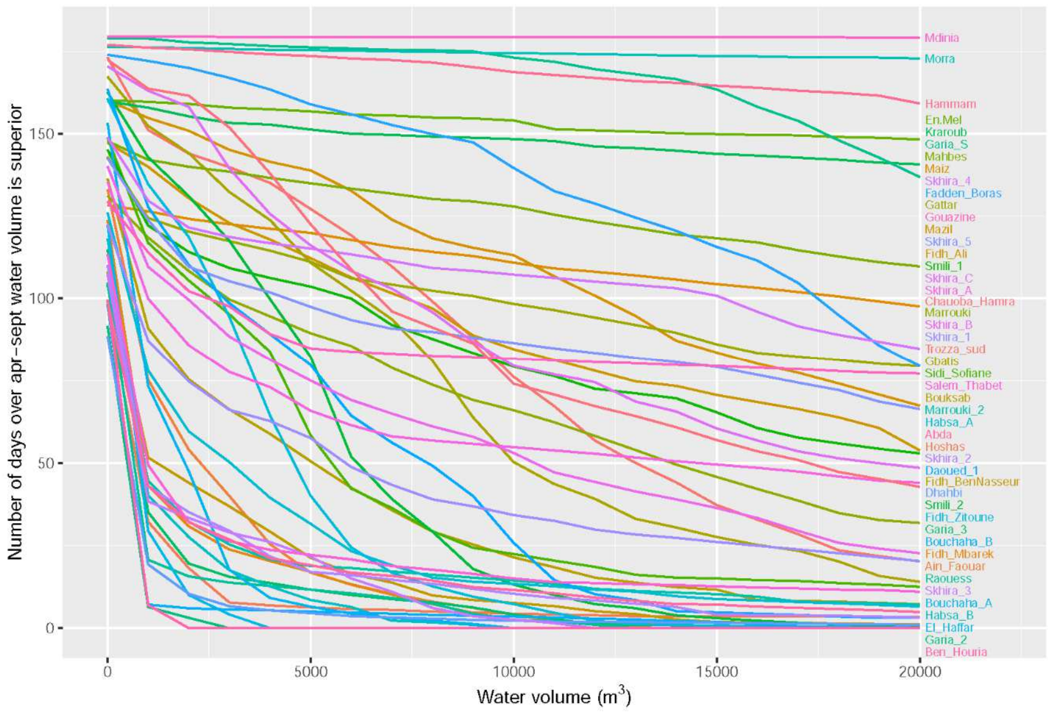

Figure 7: Mean number of days during dry season over 2007-2014 water availability remains above a designated volume for 48 reservoirs

On these 20 lakes, water availability is limited and unreliable, providing inopportune conditions to develop more intense irrigated activities but when not silted, allow for limited watering (e.g. Ain Faouar on figure 9). Several were designed for protection or recharge and appear under-dimensioned for water uses, despite farmers having planted trees and installed a pump besides these. With a mean initial capacity 44,000 m^3, many lakes are unable to hold water for any length of time, due to low depths and greater exposure to evaporation. Other larger lakes, suffered from progressive silting (Bouchaha B, Garia 3, Haffar) or like Hoshas (130,000 m^3) experienced very short floods due to high infiltration. Figure 7 highlights how water availability patterns vary rapidly when lowering the thresholds, i.e. for very small lakes (Habsa A and Fidh Zitoune) water availability around 2000 m^3 rises significantly pointing to reliable but limited water volumes. A further four lakes would reach this lower threshold of 2000 m^3 (figure 8). Conversely, where agricultural water needs were greater (e.g. 10,000 m^3 for at least 45 days), 6 additional lakes would not reach this raised target.

3.3.2. Good water availability

The 7 lakes in this category displayed water availability exceeding 5000 m^3 for more than 4.5 months during the 6 dry months, (i.e. over 75% of days). With a mean initial capacity of 1 Mm^3, these lakes support the notion that storage is determinant in semi-arid areas where floods are rare. However, exceptions exist, with El Maiz suffering despite its similar capacity (500,000 m^3) from greater water insecurity (variation coefficient = 0.97). Conversely Fadden Boras with its modest size (84,000 m^3) displayed in the absence of silting reduced

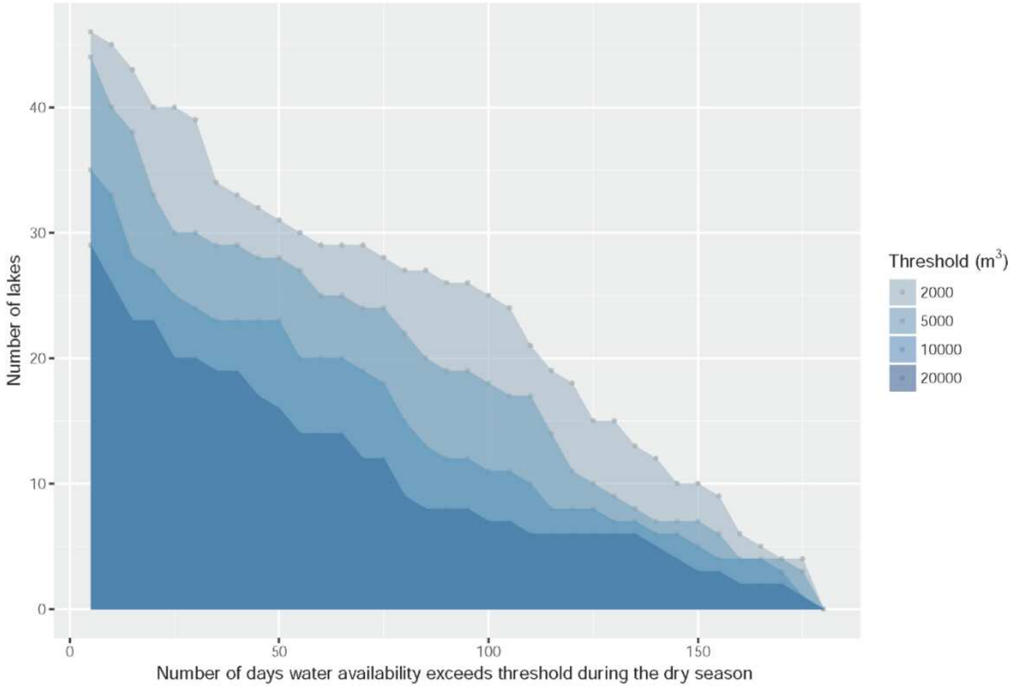

Figure 8: Number of lakes where water availability exceeds a given threshold for a number of days during dry seasons over 2007-2014

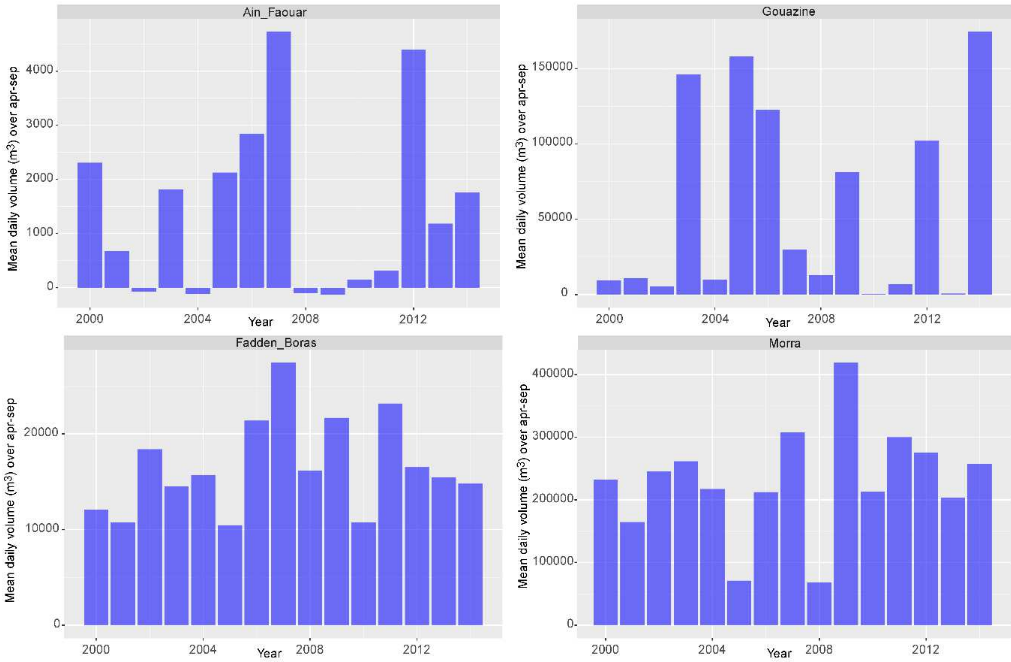

Figure 9: Simulated water availability on 4 lakes based on water withdrawals of 4100 m^3/month

variability and field visits confirmed its reliable availability. The mean availability of lakes is indeed only partly correlated ($R^2 = 0.6$) with the maximum capacity of lakes, due to the influence of the rainfall variability and differences in runoff coefficients and lake characteristics (notably high infiltration) (Ogilvie et al., 2016).

These lakes remain affected by interannual variability (figure 5), but not to the point of affecting local irrigation practices. Significantly, these lakes are the ones which can realistically provide year-round irrigation, i.e. support farmers through the critical dry periods in line with their objective in many semi-arid regions. Figure 8 highlights the modest decline in the number of these lakes if agricultural water availability requirements (in terms of volume or number of days) increase.

3.3.3. Unreliable water availability

These 21 lakes display the greatest uncertainties over water availability and fail to meet the required threshold between 1.5 and 4.5 months out of the 6 dry months. With a mean capacity of 129,000 m^3 these lakes include large lakes (Gouazine and El Maiz 230,000 m^3 and 500,000 m^3 respectively) whose average resources largely exceed the threshold (figure 5). However, these lakes suffer from significant variability and extended periods where resources become insufficient to meet these basic watering demands (figure 9). Years where availability is good, more intense localised irrigation of vegetables becomes possible, but farmers must compose with this uncertainty through other resources, be they physical (other watering points) or economic (means to purchase cisterns). As mentioned earlier, silting uncertainties were high for 13 of these lakes indicating the sites where updating topographic surveys may provide the most benefit (Ogilvie et al., 2016).

3.4. Wider socio-hydrological drivers

No correlations were observed between water availability and water use levels assessed as the number of fruit trees grown or number of pumps around lakes (figure 12). These discrepancies between water use and availability classes of each lake illustrated in figure 10 confirmed the need to look beyond purely hydrological factors.

3.4.1. Economic water access difficulties

Only 43% of lakes were equipped with motor pumps while on 23% of lakes, withdrawals consisted of occasional cisterns. The number of motor pumps ranged between 1 and 7 (mean=2.5), but across all 56 lakes the average number reduced to barely 1 per lake (figure 11). Their presence reduced since 2005 on 19% of lakes due to irreparable damages or the decline in irrigated activities (En Mel) but on others (33%), additional pumps had been acquired and replaced over time, signalling a continued or increased interest in the lake's resources by farmers or local projects. A noteworthy 27% of pumps were out of order at the time of visit, due to lack of regular maintenance or direct damage from floods. The absence of spare parts and difficulties to cover repair costs led to extended periods before pumps were repaired.

Over half (54%) of these pumps were provided by the government following the construction of the lakes, while the others had been purchased by farmers who shared the costs with 2-3 brothers or cousins. These were typically wealthier exploitations having inherited large plots of land, or farmers who had additional external resources (regular employment, or family cash flows), though a third of the private pumps had been purchased without such assistance. Credits are notably difficult to obtain due to the absence of official land titles (*titre bleu*) on 73% of exploitations surveyed.

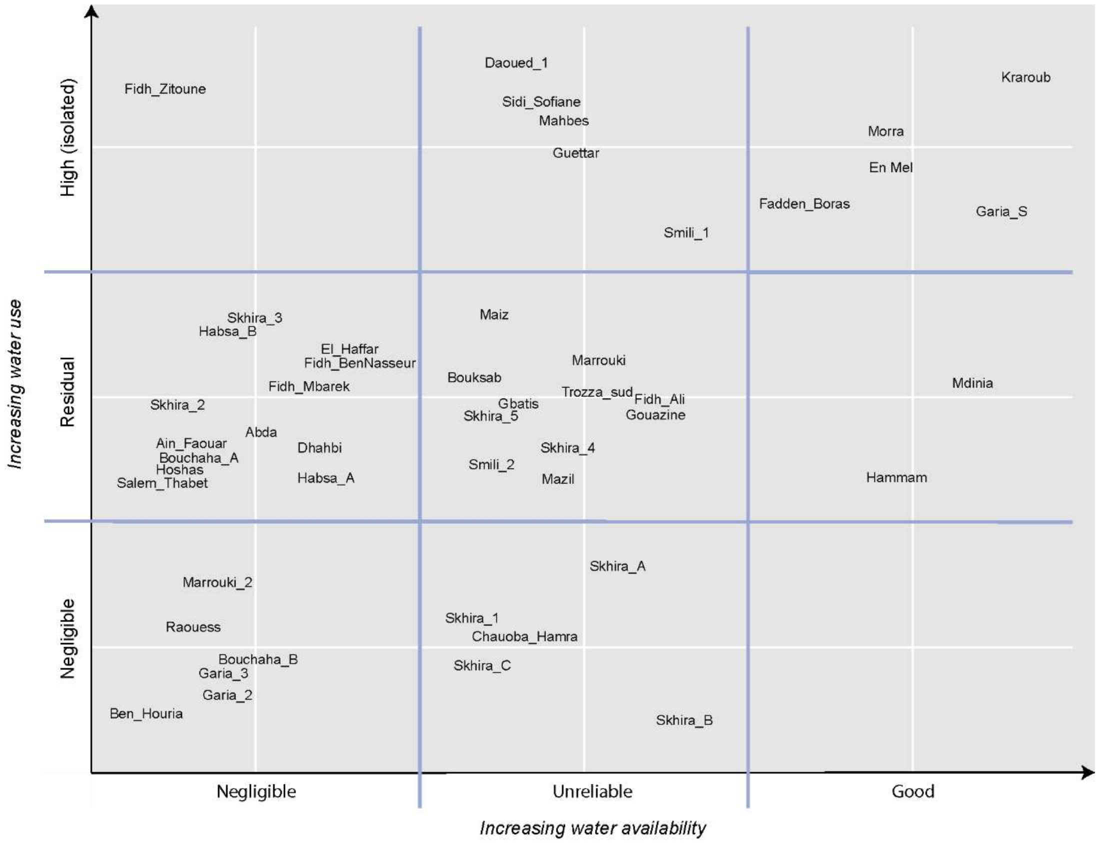

Figure 10: Representation of water availability and water uses for 48 small reservoirs according to their typology classes (precise location within the 9 squares is figurative)

3.4.2. Managing hydrological uncertainty

Farmers faced with uncertainty over water resources variability managed in certain instances to develop successful enterprises due partly to their ability to deal with water shortages. To save 1 ha of fruit trees, farmers reported needing 10 cisterns of 3000-4000 litres 2-5 times per year, representing a cost of 500DT-1250DT (1DT=0.5€ at the time) depending on rainfall and the age of the trees. These additional costs were difficult to bear by many farmers who lost part of their younger fruit trees. 60% of farmers interviewed had attempted market gardening but more than half of these ceased after losing their first crop. Limited capabilities (Sen, 1999) affects the willingness to take on risks and most users around these lakes now focus exclusively on olive and other fruit trees. Uncertainties can also prevent farmers from planting or lead them to reduce investments, e.g. applying minimal inputs hence reducing their production levels (Khlifi et al., 2010; Mugabe et al., 2003). Conversely, farmers with increased financial resilience and ability to access alternate water supplies, such as nearby wells (15 farmers) or cisterns (17 farmers), were capable of bearing these risks and developed greater irrigated activities.

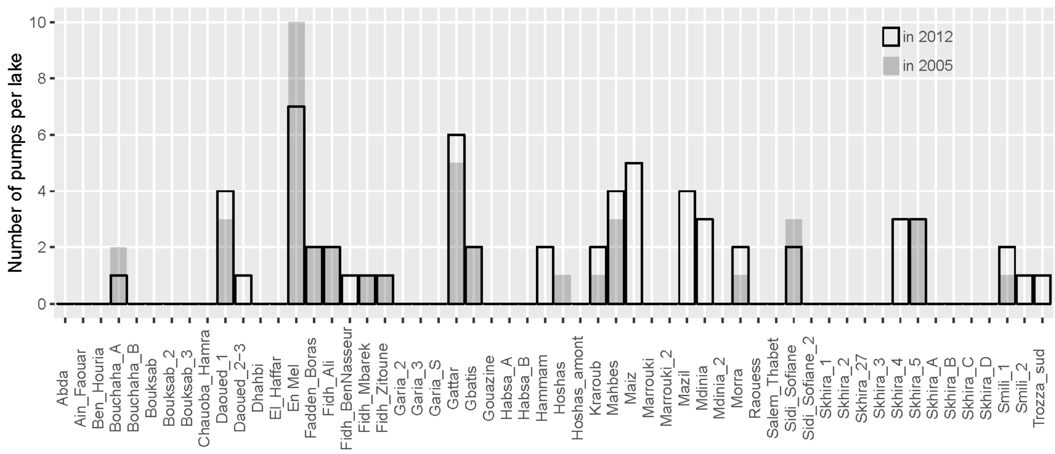

Figure 11: Number of motor pumps in 2005 (on 21 lakes) and 2012 (on 56 lakes)

3.4.3. Local water mismanagement

The limited number of pumps were shared between 2.9 beneficiaries on average, though sometimes up to 8 initially, and were to be managed through water user associations (WUAs) as requested by the government. Over 22 reservoirs, 11 had formally created an association but by 2014 all had dissolved, due to conflicts, the declining number of users, or pump failures. On other lakes, WUAs had not been created due to the low number of users and the existence of family ties. Frequent conflicts were reported, often due to the heads of WUAs unfairly restricting access to the pump (Kraroub, Maiz), or even preventing access to the lake to riparian families, entitled to the resource according to the traditional bind between land and water rights. In many cases, the position of head of WUA (and often dam operator) were given to local government employees living on site, or others with close links to the former ruling party, the *Rassemblement constitutionnel démocratique* (RCD). The importance of ties with government officials and bribes were highlighted by several interviewees and allegedly influenced the number of pumps but also tree saplings that farmers benefited from.

Over time, several government pumps became private, due to members acquiring these after reportedly paying for repairs. Other farmers resorted to private pumps shared amongst family members, but conflicts endure over water turns or maintenance and repair costs. In the absence of an active WUA, management and access to the lake is done through informal gatherings, where established influences (dam operator and/or head of WUAs) continue to play a role. The absence of clear management leads to unregulated withdrawals, where farmers reported withdrawing what they can afford while water is available, replicating the tragedy of the commons (Hardin, 1968) already observed (Selmi and Talineau, 1994). The resulting rapid decline in resources led to certain farmers calling for instating control and fees over water access but coordinated by an external government engineer.

3.4.4. Local participation and development strategy

While farmers agreed (Gouazine) or even requested (Fidh Mbarek, Guettar and Fidh Zitoune) certain lakes, others regretted not being consulted on their interest for a dam, which was eventually imposed, sometimes at the expense of their land and livelihoods. Out of 29 exploitations with land under the 22 lakes (and 12 with land titles to prove it), only 2 reported obtaining some compensation (Garia S, El Kraroub), generating disaffection for the project. Government strategies to develop water use appear somewhat fuzzy (Riaux et al., 2014), and in many cases argue that irrigation remained merely an “implicit" objective (Selmi and Zekri, 1995), behind the priority protection of downstream infrastructure. Criteria in project documents referred to physical parameters however failed to include social selection criteria relating to water use despite the stated irrigation objectives. Farmers confirmed no pre-assessment to identify local resources and challenges was carried out, reducing ownership and participation by end users (Habi and Morsli, 2011; Selmi and Talineau, 1994; Selmi and Zekri, 1995; Talineau et al., 1994; Wisser et al., 2010). Numerous incoherences were also observed in the siting of dams (Chaouba El Hamra, El Marrouki 2) where the clear absence of beneficiaries around the lake appears to contradict the stated objectives of developing irrigation. On others, no pumps or trees were provided, or sometimes only at a much later stage therefore losing out on the impetus created by the construction of the lake intended for irrigation. Larger irrigation projects (Morra and Kraroub) never materialised, due for instance to a failed electrification strategy, leading to a built, yet inoperative pumping station. Incoherences were also reported by farmers in policies forbidding lake users to sell market gardening products (Gbatis, En Mel and Mahbes) or advising farmers that water use would be forbidden to favour recharge (Hoshas) but only after the construction, placing undue expectations on the lake.

3.4.5. Limited ongoing government assistance

15 out of 22 lakes investigated had benefited from a pump, provided by the government or the funding body (e.g. EU project) and 45% of farmers had obtained fruit trees saplings. Farmers interviewed expected further support however and several regularly placed requests with the local authorities for subsidies for additional pumps, bergater piping or repairs to the dam, whose maintenance over time is poorly budgeted (Selmi and Talineau, 1994). In the remote Merguellil upper catchment, public action for development is limited compared to the downstream Kairouan plain, and is compensated for through subventions and individualised small grants (Riaux et al., 2014). Government assistance appears to have been too limited and punctual for many users to make the transition from traditional rainfed activities to irrigated activities, which demand additional investments and knowledge (Oweis and Hachum, 2006; Selmi and Talineau, 1994; Zairi et al., 2005). Monitoring over time by authorities may have also helped solve some of the incongruities and mismanagement observed around lakes. The continued reference to the local government by farmers emphasised how engrained the government’s presence is, possibly as a result of the historically interventionist government. This also seemed to reflect a posture, whereby farmers are merely managing a government lake where they gained rights, instead of appropriating their lake.

3.4.6. Conflicting livelihood strategies

Of those who abandoned market gardening, 19 stated that water supply was the dominant constraint however 15 identified other reasons, which included the costs and low profits obtained, the intense labour and the presence required. Small farmers notably struggled to cope financially until the harvest and with the minimal return on investment from fruit trees in the first years, leading them to pursue complementary livelihoods. A subset of farmers (7) with large herds of sheep (between 50 and 60) and significant surface area (10-60 ha) of cereals showed no real interest in intensifying their fruit farming activities, preferring to rely on traditional agricultural livelihoods. Other farmers had already started to diversify their income due to land surface area reducing through inheritance and soil fertility declining over time, and work as labourers (CNEA, 2006; Selmi et al., 2001). Many, when they have interesting opportunities (including abroad in Libya or Cameroon) pursue these activities and when contracts are scarce and/or water levels were high, choose to focus on agriculture and seek to intensify their production (market gardening, fertilisers, etc.). Out of 28 people who previously had a secondary source of income, 25 continue to have a secondary activity, implying that only three people were able to move towards agriculture exclusively, here high value fruit (cherry, fig, apricots) and some market gardening.

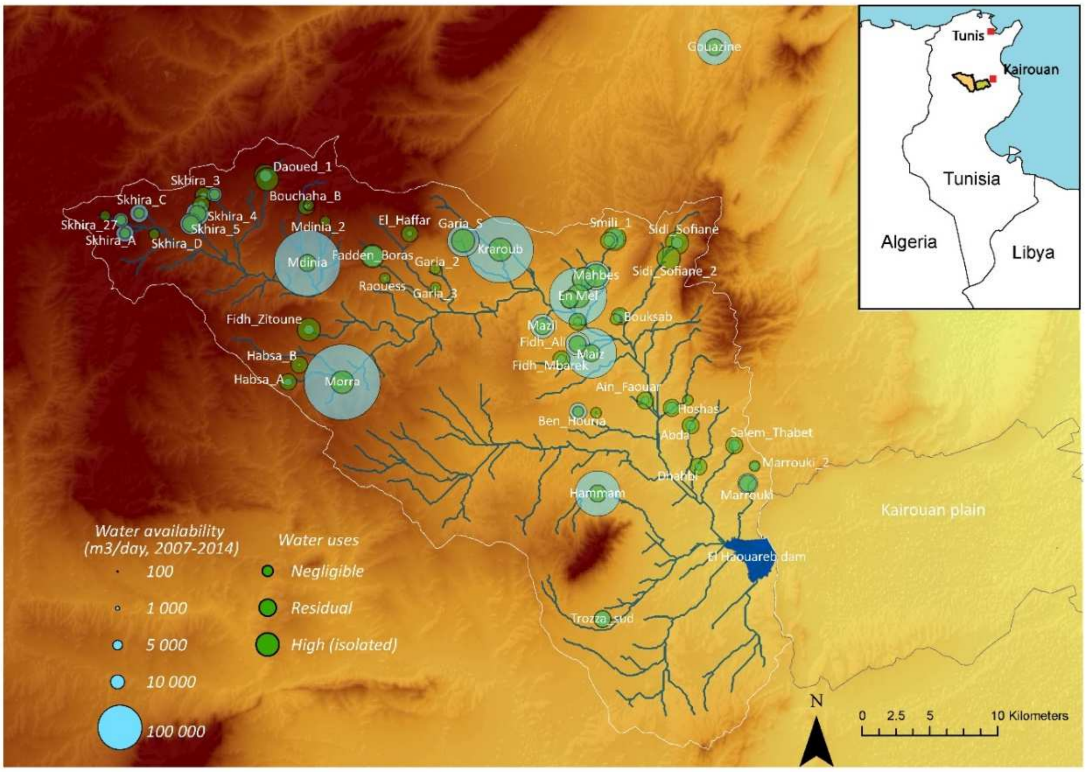

Figure 12: Map of interannual mean water availability (2007-2014) and agricultural water use levels per lake

4. Conclusions

The multi-scale, interdisciplinary approach developed here highlighted the vast disparities in the benefits and practices between lakes, farmers and over time. Diachronic perspectives highlighted crop diversification and an increase in fruit trees, supported in part by watering from the lakes. Olive harvests provide non-negligible revenue to families, and during good years, farmers can develop limited lucrative activities. Isolated successful enterprises based around intensive fruit farming were also observed. The wide framework also identified support to livestock, nearby wells and immaterial benefits.

Attempts to develop market gardening and intensifying fruit farming on 56% of lakes bear witness to the level of interest in this additional resource, but most farmers were deceived due to the unfavourable hydro-meteorological conditions. Exploiting the Landsat-derived water availability patterns provided unprecedented insights into the hydrological constraints on 86% of small lakes. On some of the smallest lakes, due to their size or rapid infiltration, their initial potential was already negligible and communication with the riparian communities would have avoided disappointments and associated disaffection. On lakes where volumes can be significant and irrigated activities can be developed, farmers must be equipped with strategies to cope with the variability and associated uncertainty for the lake to cease to be both a “help and a threat”. For most this was limiting, and led to the loss of production, while those with sufficient economic resilience or other water supplies survived the droughts. Though a limiting condition, water availability was indeed not a sufficient condition to understand the disparities in practices. On lakes where water availability is high, individual successes are reported and again occurred as a result of individual capabilities. Inadequate ongoing government support to develop and structure agricultural activities and water management limited the number of beneficiaries, due largely to problems over access to pumps, pipes, repairs and to WUA failures. Farmers were in certain cases excluded from the start (Selmi and Talineau, 1994) and others more subtly over time, through conflicts, mismanagement and appropriation of the pumps. Where the local government was proactive this led to wider levels of exploitation compared to other similar lakes, but benefits remained confined to a select few.

Investments in small reservoirs have supported remote rural areas, affected by erosion, poor soils and low and irregular rainfall, albeit with often low equity and incoherences. They probably contributed to slow the inevitable fate of rural exodus, and investments helping local upstream smallholders (Vincent, 2003) should be encouraged. The majority of small reservoirs which depend on erratic rainfall volumes are however limited in their ability to develop irrigated agriculture on any significant scale. Lakes can support dry spells during the rainy season, and on good rainfall years intensification during dry months if supported adequately to optimise production and minimise risks could be performed. However fundamentally small reservoirs, despite gradual shifts in the discourse (Venot and Krishnan, 2011) are designed for supplementary irrigation and their limited storage does not address the years when rainfall is low, preventing a long term transition to irrigated agriculture. In any case, reservoirs by capturing silt have a dedicated lifespan and must not be perceived as a perennial solution. 30 years on, complementary strategies are required to support the seeds sown by these previous water and soil conservation programmes.

Acknowledgements

We thank all the people interviewed for their vital contributions and hospitality. We also gratefully acknowledge the collaboration from the Direction Générale de l'Aménagement et de la Conservation des Terres Agricoles (DG ACTA) and Direction Générale des Ressources en Eau (DGRE) in Tunis and local representatives at the Kairouan and Siliana Commissariat Régional au Développement Agricole (CRDA). These works were partly financed by the ANR AMETHYST and SICMED DYSHYME projects.

References

Albergel, J., Rejeb, N., 1997. Les lacs collinaires en Tunisie : Enjeux, Contraintes et Perspectives. Comptes rendus l'Académie d'agriculture Fr. 83, 77–88.

Ayantunde, A.A., Cofie, O., Barron, J., 2018. Multiple uses of small reservoirs in crop-livestock agro-ecosystems of Volta basin: Implications for livestock management. Agric. Water Manag. 204, 81–90. https://doi.org/10.1016/j.agwat.2018.04.010

Beaud, S., 1996. L'usage de l'entretien en sciences sociales. Plaidoyer pour l'entretien ethnographique. Politix 9, 226–257. https://doi.org/10.3406/polix.1996.1966

Becker, H.S., 1998. Tricks of the trade : how to think about your research while you're doing it. University of Chicago Press.

Braden, J.B., Brown, D.G., Dozier, J., Gober, P., Hughes, S.M., Maidment, D.R., Schneider, S.L., Schultz, P.W., Shortle, J.S., Swallow, S.K., Werner, C.M., 2009. Social science in a water observing system. Water Resour. Res. 45. https://doi.org/10.1029/2009WR008216

CNEA, 2006. Etude d'impact des travaux de conservation des eaux et du sol dans le gouvernorat de Kairouan.

Collard, A.-L., Burte, J., 2014. The non-adherence of farmers in the Sertão to the conversion of their agricultural model [La non-adhésion des agriculteurs du sertão brésilien à la conversion de leur Modèle agricole]. Etud. Rurales 194, 219–235.

de Fraiture, C., Kouali, G.N., Sally, H., Kabre, P., 2014. Pirates or pioneers? Unplanned irrigation around small reservoirs in Burkina Faso. Agric. Water Manag. 131, 212–220. https://doi.org/10.1016/J.AGWAT.2013.07.001

Denzin, N.K., Lincoln, Y.S., 1994. Handbook of qualitative research. Sage Publications.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J.L., Blöschl, G., 2013. Socio-hydrology: conceptualising human-flood interactions. Hydrol. Earth Syst. Sci. 17, 3295–3303. https://doi.org/10.5194/hess-17-3295-2013

Dridi, B., Bourges, J., Collinet, J., Auzet, A. V, Garreta, P., 2001. Impact des aménagements sur la ressource en eaux dans le bassin du Merguellil (Tunisie centrale), in: Servat, E., Albergel, J. (Eds.), Hydrologie Des Régions Méditerranéennes. UNESCO, IRD, Montpellier, pp. 192–203.

Falkenmark, M., 1977. Water and Mankind: A Complex System of Mutual Interaction. Ambio 6, 3–9. https://doi.org/10.2307/4312233

Faulkner, J.W., Steenhuis, T., van de Giesen, N., Andreini, M., Liebe, J.R., 2008. Water use and productivity of two small reservoir irrigation schemes in Ghana's upper east region. Irrig. Drain. 57, 151–163. https://doi.org/10.1002/ird.384

Forkel, M., Carvalhais, N., Verbesselt, J., Mahecha, M., Neigh, C., Reichstein, M., 2013. Trend Change Detection in NDVI Time Series: Effects of Inter-Annual Variability and Methodology. Remote Sens. 5, 2113–2144. https://doi.org/10.3390/rs5052113

Gay, D., 2004. Fonctionnement et bilan de retenues artificielles en Tunisie: approche hydrochimique et isotopique (PhD). Université Paris XI, France.

Glaser, B.G., Strauss, A.L., 1967. The Discovery of Grounded Theory: Strategies for Qualitative Research. Routledge, New York. https://doi.org/10.2307/2575405

Habi, M., Morsli, B., 2011. Contraintes et perspectives des retenues collinaires dans le Nord-Ouest algérien. Sécheresse 22, 49–56. https://doi.org/10.1684/sec.2011.0293

Hale, R.L., Armstrong, A., Baker, M. a, Bedingfield, S., Betts, D., Buchert, M., Crowl, T., Dupont, R.R., Ehleringer, J.R., Flint, C., Grant, J., Hinners, S., Horsburgh, J.S., Jones, A.S., Licon, C., Null, S.E., Odame, A., Diane, E., Rosenberg, D., Runburg, M., Stoker, P., Strong, C., 2015. iSAW : Integrating Structure , Actors , and Water to study socio-hydro-ecological systems. Earth's Futur. 3, 110–132. https://doi.org/10.1002/2014EF000295.

Hardin, G., 1968. The tragedy of the commons. Science (80-.). 162, 1243–8. https://doi.org/10.1126/science.162.3859.1243

Khlifi, S., Ameur, M., Mtimet, N., Ghazouani, N., Belhadj, N., 2010. Impacts of small hill dams on agricultural development of hilly land in the Jendouba region of northwestern Tunisia. Agric. Water Manag. 97, 50–56. https://doi.org/10.1016/j.agwat.2009.08.010

King, E.G., O'Donnell, F.C., Caylor, K.K., 2012. Reframing hydrology education to solve coupled human and environmental problems. Hydrol. Earth Syst. Sci. 16, 4023–4031. https://doi.org/10.5194/hess-16-4023-2012

Kingumbi, A., 2006. Modélisation hydrologique d'un bassin affecté par des changements d'occupation. Cas du Merguellil en Tunisie Centrale. Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis.

Lacombe, G., 2007. Evolution et usages de la ressource en eau dans un bassin versant amenagé semi-aride. Le cas du Merguellil en Tunisie Centrale. Université Montpellier II.

Le Goulven, P., Leduc, C., Bachta, M.S., Poussin, J.-C., 2009. Sharing scarce resources in Mediterranean river rasin: Wadi Merguellil in Central Tunisia, in: Molle, F., Wester, F. (Eds.), River Basin Trajectories: Societies, Environments and Development. CAB International, pp. 147–170.

Leduc, C., Ben Ammar, S., Favreau, G., Beji, R., Virrion, R., Lacombe, G., Tarhouni, J., Aouadi, C., Zenati Chelli, B., Jebnoun, N., Oi, M., Michelot, J.L., Zouari, K., 2007. Impacts of hydrological changes in the Mediterranean zone: environmental modifications and rural development in the Merguellil catchment, central Tunisia. Hydrol. Sci. J. 52, 1162–1178. https://doi.org/10.1623/hysj.52.6.1162

Longhurst, R., 2009. Interviews: In-Depth, Semi-Structured. Int. Encycl. Hum. Geogr. 580–584. https://doi.org/10.1016/B978-008044910-4.00458-2

Massuel, S., Riaux, J., Molle, F., Kuper, M., Ogilvie, A., Collard, A.L., Leduc, C., Barreteau, O., 2018. Inspiring a Broader Socio-Hydrological Negotiation Approach With Interdisciplinary Field-Based Experience. Water Resour. Res. https://doi.org/10.1002/2017WR021691

Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. a., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., Belyaev, V., 2013. Panta Rhei - Everything Flows: Change in hydrology and society - The IAHS Scientific Decade 2013 - 2022. Hydrol. Sci. J. 58, 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Montoroi, J., Grunberger, O., Nasri, S., 2002. Groundwater geochemistry of a small reservoir catchment in Central Tunisia. Appl. Geochemistry 17, 1047–1060. https://doi.org/10.1016/S0883-2927(02)00076-8

Mugabe, F.T., Hodnett, M.G., Senzanje, A., 2003. Opportunities for increasing productive water use from dam water: a case study from semi-arid Zimbabwe. Agric. Water Manag. 62, 149–163. https://doi.org/10.1016/S0378-3774(03)00077-5

Mushtaq, S., Dawe, D., Hafeez, M., 2007. Economic evaluation of small multi-purpose ponds in the Zhanghe irrigation system, China. Agric. Water Manag. 91, 61–70. https://doi.org/10.1016/j.agwat.2007.04.006

Ogilvie, A., 2015. Upscaling water availability and water use assessments in hydro-sociosystems: the small reservoirs of the Merguellil catchment (Central Tunisia) (PhD). Université de Montpellier and King's College London.

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., Calvez, R., 2018. Surface water monitoring in small water bodies: potential and limits of multi-sensor Landsat time series. Hydrol. Earth Syst. Sci. Discuss. 1–35. https://doi.org/10.5194/hess-2018-19

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., Calvez, R., 2016. Assessing Floods and Droughts in Ungauged Small Reservoirs with Long-Term Landsat Imagery. Geosciences 6, 42. https://doi.org/10.3390/GEOSCIENCES6040042

Olivier de Sardan, J.-P., 2005. Anthropology and development : understanding contemporary social change. Zed Books.

Ostrom, E., 1990. Governing the commons: The evolution of institutions for collective action, Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press. https://doi.org/10.1017/CBO9781316423936

Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric. Water Manag. 80, 57–73. https://doi.org/10.1016/j.agwat.2005.07.004

Pande, S., Sivapalan, M., 2016. Progress in socio-hydrology: a meta-analysis of challenges and opportunities. Wiley Interdiscip. Rev. Water. https://doi.org/10.1002/wat2.1193

Riaux, J., 2013. Engager la construction d'un regard sociohydrologique : des archives catalyseurs de l'interdisciplinarité. Natures Sci. Sociétés 21, 15–23. https://doi.org/10.1051/nss/2013061

Riaux, J., Massuel, S., 2014. Construire un regard sociohydrologique (2). Le terrain en commun, générateur de convergences scientifiques. Natures Sci. Sociétés 22, 329–339. https://doi.org/10.1051/nss/2014046

Riaux, J., Ogilvie, A., Jenhaoui, Z., 2014. Les retenues collinaires font-elles ressource? Réflexions à partir de la Tunisie Centrale, in: 6e Colloque de La T.M.A for H.S.E.S. Monastir, Tunisia.

Selmi, S., Sai, M.B., Hammami, M., 2001. La valorisation des ressources en eau aléatoires et non pérennes par le développement de l'olivier autour des lacs collinaires en Tunisie. Sécheresse 12, 45–50.

Selmi, S., Talineau, J.-C., 1994. Des lacs collinaires pour un développement durable en Tunisie semi-aride : Systèmes irrigués. Les Cah. la Rech. 37, 33–46.

Selmi, S., Zekri, S., 1995. Evaluation économique et environnementale des lacs collinaires en Tunisie. Le cas d'El Gouazine (Ousslatia - Kairouan), in: Pontanier, R. (Ed.), L'homme Peut Il Refaire Ce Qu'il a Défait. John Libbey Eurotext, pp. 439–448.

Sen, A., 1999. Commodities and capabilities. Oxford University Press.

Sivakumar, B., 2012. Socio-hydrology: not a new science, but a recycled and re-worded hydrosociology. Hydrol. Process. 26, 3788–3790. https://doi.org/10.1002/hyp.9511

Sivapalan, M., Savenije, H.H.G., Blöschl, G., 2012. Socio-hydrology: A new science of people and water. Hydrol. Process. 26, 1270–1276. https://doi.org/10.1002/hyp.8426

Talineau, J.C., Selmi, S., Alaya, K., 1994. Lacs collinaires en Tunisie semi-aride. Sécheresse 5, 251–256.

Thompson, S.E., Sivapalan, M., Harman, C.J., Srinivasan, V., Hipsey, M.R., Reed, P., Montanari, A., Blöschl, G., 2013. Developing predictive insight into changing water systems: Use-inspired hydrologic science for the anthropocene. Hydrol. Earth Syst. Sci. 17, 5013–5039. https://doi.org/10.5194/hess-17-5013-2013

Venot, J.-P., Cecchi, P., 2011. Valeurs d'usage ou performances techniques : comment apprécier le rôle des petits barrages en Afrique subsaharienne ? Cah. Agric. 20, 112–117. https://doi.org/10.1684/agr.2010.0457

Venot, J.-P., Hirvonen, M., 2013. Enduring Controversy: Small Reservoirs in Sub-Saharan Africa. Soc. Nat. Resour. 26, 883–897. https://doi.org/10.1080/08941920.2012.723306

Venot, J.P., Krishnan, J., 2011. Discursive framing: Debates over small reservoirs in the Rural South. Water Altern. 4, 316–324.

Vincent, L.F., 2003. Towards a smallholder hydrology for equitable and sustainable water management. Nat. Resour. Forum 27, 108–116. https://doi.org/10.1111/1477-8947.00046

Wesselink, A., Kooy, M., Warner, J., 2017. Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. Wiley Interdiscip. Rev. Water. https://doi.org/10.1002/wat2.1196

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Schumann, A.H., Vörösmarty, C.J., 2010. The significance of local water resources captured in small reservoirs for crop production - A global-scale analysis. J. Hydrol. 384, 264–275. https://doi.org/10.1016/j.jhydrol.2009.07.032

Xu, H., 2006. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. Int. J. Remote Sens. 27, 3025–3033. https://doi.org/10.1080/01431160600589179

Zairi, M., Karray, I., Ben Dhia, H., 2005. Evaluation participative de l'impact des travaux de conservation des eaux et des sols (CES) dans le région de Sidi M'hadheb (Sud-Est tunisien). Sécheresse 16, 53–60.

700 ## Appendix A. Supplementary materials

701 Table A.1: Water availability and use characteristics for each lake

702

Category	Lake	Initial capacity (m^3)	Mean annual availability (m^3/day, 2007-2014)	Withdrawals	Nb of pumps	Nearby wells	Initial objectives
Negligible benefits	Ben Houria	17,000	341	Y	0	N	Protection (Kairouan)
	Bouchaha B	34,000	620	Y	0	N	Irrigation
	Bouksab 2	N/A	N/A	Y	0	N	Protection (road)
	Bouksab 3	N/A	N/A	Y	0	N	Protection (road)
	Chaouba Hamra	120,000	15,876	N	0	N	Irrigation
	Garia 2	19,000	403	Y	0	N	Recharge
	Garia 3	25,000	1,239	Y	0	N	Recharge
	Hoshas amont	N/A	N/A	N	0	N	N/A
	Marrouki 2	56,000	3,691	N	0	N	Irrigation
	Raouess	18,000	1,285	N	0	Y	N/A
	Skhira 1	181,000	11,494	N	0	N	Protection
	Skhira 27	N/A	N/A	N	0	N	Protection
	Skhira A	72,000	16,277	Y	0	N	Protection
	Skhira B	120,000	11,269	N	0	N	Protection
	Skhira C	52,000	16,896	N	0	N	Protection
	Skhira D	N/A	N/A	N	0	N	Protection
Residual benefits	Abda	37,000	4,972	N	0	Y	Recharge
	Ain Faouar	66,000	3,309	Y	0	Y	Recharge
	Bouchaha A	18,000	1,560	Y	1	N	Irrigation
	Bouksab	55,000	8,152	Y	0	Y	Irrigation
	Dhahbi	26,000	2,799	N	0	Y	Recharge
	El Haffar	30,000	1,720	Y	0	N	N/A
	Fidh Ali	134,000	30,092	Y	2	N	Irrigation
	Fidh Ben Nasseur	47,000	3,751	Y	1	Y	Protection (plots)
	Fidh Mbarek	53,000	4,287	Y	1	N	Irrigation
	Gbatis	106,000	17,598	Y	2	N	Irrigation
	Gouazine	237,000	65,435	Y	0	Y	Irrigation
	Habsa A	50,000	3,964	Y	0	N	Irrigation
	Habsa B	35,000	912	Y	0	N	Irrigation
	Hammam	850,000	107,826	Y	2	N	Irrigation
	Hoshas	130,000	7,365	Y	0	Y	Recharge

	Maiz	500,000	132,408	Y	5	N	Irrigation
	Marrouki	153,000	21,179	Y	0	Y	Recharge
	Mazil	104,000	30,438	Y	4	N	N/A
	Mdinia	1,200,000	229,921	Y	3	N	N/A
	Mdinia 2	N/A	N/A	Y	0	N	N/A
	Salem Thabet	63,000	6,426	N	0	Y	Recharge
	Skhira 2	38,000	2,748	Y	0	N	Protection
	Skhira 3	79,000	3,238	Y	0	N	Protection
	Skhira 4	160,000	28,526	Y	3	N	Protection
	Skhira 5	60,000	23,085	Y	3	Y	Protection
	Smili 2	35,000	6,333	Y	1	N	Irrigation
	Trozza Sud	50,000	13,760	Y	1	N	Irrigation
Isolated, high benefits	Daoued 1	95,000	7,350	Y	4	N	N/A
	Daoued 2 3	350,000	N/A	Y	1	N	N/A
	En Mel	1,000,000	172,073	Y	7	N	Recharge
	Fadden Boras	94,000	21,742	Y	2	N	N/A
	Fidh Zitoune	40,000	5,244	Y	1	N	N/A
	Garia S	1,500,000	53,483	Y	0	N	N/A
	Guettar	150,000	28,126	Y	6	Y	Irrigation
	Kraroub	1,590,000	229,970	Y	2	N	Irrigation
	Mahbes	180,000	42,863	Y	4	N	Irrigation
	Morra	705,000	302,106	Y	2	N	Irrigation
	Sidi Sofiane	40,000	6,696	Y	2	Y	Irrigation
	Sidi Sofiane 2	N/A	N/A	Y	0	N	Irrigation
	Smili 1	130,000	19,677	Y	2	N	Irrigation
			Number of lakes where present	*44*	*23*	*13*	

Table 1: Categorisation of 56 small reservoirs based on agricultural water uses

Lake Category	Negligible benefits	Residual benefits	Isolated, high benefits
Number of lakes	16	27	13
Initial capacity			
Min	17,000	18,000	40,000
Mean	181,000	1,200,000	1,590,000
Max	65,000	166,000	490,000
Mean annual availability (m^3/day, 2007-2014)			
Min	340	900	5,200
Mean	16,900	230,000	302,000
Max	7,200	29,300	80,800
Mean number of pumps	0	1.1	2.5
Fruits trees/farm	N/A	300	900
Market gardening/farm	N/A	Up to 0.5 ha	Up to 2.5 ha
Withdrawals (m^3/month/lake)	0	Up to 1200	Up to 4100