Shifting or drifting?

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Shifting or drifting? The crisis-driven advancement and failure of private smallholder irrigation from sand river aquifers in southern arid Zimbabwe

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ABSTRACT

In recent years more recognition is given to the benefits and risks of private smallholder irrigation development across sub-Saharan Africa. It is acknowledged for its capacity to adapt to local circumstances and challenges. This study assesses the heterogeneous character of private smallholder irrigation in the challenging environment of southern arid Zimbabwe, where family farms operate along sand river aquifers, forming a reliable natural storage of shallow groundwater. It investigates the drivers, characteristics, obstacles and adaptive capacity of this yet undocumented form of private irrigation in a historically marginalised area, and in particular also the discontinuation of these informal irrigation ventures. The research combines results from analysing satellite images, and quantitative and qualitative field work, whereby a social-ecological system perspective is applied.

This form of private smallholder irrigation is distinct from most other documented cases in sub-Saharan Africa. First, because of the unique interrelation between the water source, technology need and fuel-dependency in an economically marginalised area. Second, because drivers for the emergence of private smallholder irrigation are not market-based but crisis-driven; recurrent droughts and frequent dry-spells, failure of collectively-managed irrigation schemes, and persistent economic instability. As a result, many families cease operations because they reach the limits of their adaptive capacity or they migrate. Those who succeed, manage to benefit from the abundance of water stored in sand rivers, the mobilisation of knowledge and cash through rural networks, and the existence of cross-border trade opportunities. However, they hardly ever pass the level of subsistence in an area where stable markets are absent. Organising potential support to private smallholder irrigation remains a challenging and disputable avenue as this might undermine its independent and adaptive nature.

1. Introduction

The need for a revised and nuanced perspective on smallholder irrigation development for enhanced crop production in sub-Saharan Africa is apparent, thereby requiring a consideration of both formal and informal irrigation (Lankford, 2009; Giordano and de Fraiture, 2014; Woodhouse et al., 2017). Formal smallholder irrigation development is mostly geared towards farmer- or agency-managed collective schemes with strong government and/or donor support. These schemes face a range of constraints in operating sustainably, and struggle to maintain or even decrease production levels (Mutambara et al., 2016). Challenges originate from a general failure to undertake collective action and a corresponding dependency on costly external support (Coward, 1986; Lankford, 2005). A cycle in which schemes function for a few seasons after rehabilitation, deteriorate, and return to disuse, is observed in several irrigation schemes in Zimbabwe (Mutambara et al., 2016). Below the radar however, many alternative forms of private smallholder irrigation have evolved, the full extent and impact of which have not yet been documented. It is estimated to be a multiple of officially recorded irrigation in terms of area (Wiggins and Lankford, 2019). Several types of private smallholder irrigation in sub-Saharan Africa have been described, including both historic and recent accounts (Bolding et al., 1996; Lankford, 2005; Ofosu et al., 2010; Namara et al., 2011; de Fraiture and Giordano, 2014; Woodhouse et al., 2017; Scoones et al., 2019). These refer to individual families who have independently established and developed irrigation, without (major) investments or support from external agencies. They mostly emerge in areas with distinct (new) market opportunities and operate with a diverse range of

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irrigation technology (Ofosu et al., 2010; Wiggins and Lankford, 2019). Although not integrated in national irrigation policies or development agenda's, private smallholder irrigation is lauded for its potential to better adapt to local circumstances and shocks, as is observed within different contexts throughout sub-Saharan Africa (Beekman et al., 2014; Woodhouse et al., 2017). Living under harsh conditions forces farming households to constantly adapt to changing circumstances and shocks, for example to droughts and changing rainfall patterns (Smucker and Wisner, 2008; Gbetibouo, 2009).

Although private smallholder irrigation can thus form a more sustainable and adaptive form of irrigated agriculture and livelihood contribution, possible negative local and downstream effects are also recognised, such as competition over land, inequitable access to technology and benefits, or over-abstraction and reduced downstream water flows (Giordano and de Fraiture, 2014; Woodhouse et al., 2017). Nevertheless, the overall development of private smallholder irrigation is regarded as advantageous and a justifiable direction for irrigation development policies (for example, the Kigali Joint Statement on Inclusive and Sustainable Farmer-led[1] Irrigation at the African green Revolution conference in 2018). To support an enabling environment for diverse groups of private irrigators, there are still two linked omissions to be addressed. First, little is yet known about the emergence and endurance of private smallholder irrigation in areas where there is an absence of strong market linkages, as opposed to the cases mentioned earlier. The second matter refers to the extent of and reasons for the discontinuation of individual farmers, which is likely to be related to the drivers for the establishment of private smallholder irrigation. When informal irrigation fails, it becomes invisible and hence conclusions and recommendations are biased towards more fortunate experiences of private irrigation (Wiggings and Lankford, 2019). Improving insights into these concerns is expected to contribute to better developing targeted and context-specific support mechanisms.

The rural areas of Matabeleland South in southern Zimbabwe are such a region that is characterised by weak markets for selling agricultural produce. Smallholder farming families live in a historically marginalised area with an arid to semi-arid climate. The region is prone to frequent droughts that lead to major crop losses. Also, recurrent political and economic instability impair food security levels, while communal irrigation systems face challenges to increase and sustain production. However, this region in the Limpopo basin is home to a major source of good quality water that is stored in shallow sand river aquifers. These unconfined groundwater layers in the sandy stream beds of ephemeral rivers have significant potential for productive use (Love et al., 2011; Acacia Water, 2019). Water has been abstracted from these aquifers by rural communities for domestic supply, livestock, fishponds and smallholder farming for a long time (Mugabe et al., 2003; Love et al., 2005; Senzanje et al., 2008; Mpala et al., 2016). They use different modes of withdrawal, mostly scoop holes, shallow wells and wellpoint systems, and sometimes aided with the construction of a sand dam (Love et al., 2005; Lasage et al., 2008; Olufayo et al., 2010; Ryan and Elsner, 2016). The potential for more intensive use is large. For example, modelling irrigation development scenarios in the Lower Mzingwane sub-catchment shows that sand river aquifers have natural storage potential for developing approximately 5000 ha of irrigated agriculture, eliminating the need to construct any costly reservoirs with potential adverse social and environmental effects (Love et al., 2011).

Despite the large irrigation potential along these ephemeral rivers, little is known to what extent this resource is currently used by private smallholder irrigators. There is limited evidence on how private farming has emerged within rural livelihood strategies along sand rivers, how rough their development trajectories might be, and whether families have dropped out of irrigated agriculture. Answers to these issues are pursued to contribute to deepening and nuancing the debate about the relevance of and possible interventions in private smallholder irrigation in sub-Saharan Africa. This study therefore looks at the emergence, development, and the discontinuation of private smallholder irrigation along two ephemeral rivers in southern Zimbabwe; the Tuli and the Shashe rivers. It aims to contribute to unravelling the diversity of private smallholder irrigation in sub-Saharan Africa, and the factors that facilitate or hinder private smallholder irrigation establishment and endurance. Private smallholder irrigation is conceptualised as a social-ecological system in order to identify the key linkages between the biophysical and socio-economic systems at different spatial and temporal scales (Anderies et al., 2004).

Section 2 introduces the study area, conceptual framework, and research methods. Section 3 presents the results, which include the characteristics of private smallholder irrigation within rural households, the dynamics and drivers of private smallholder irrigation development, the adaptive farm development strategies within social networks in a migration-economy, the challenges faced and coping mechanisms adopted, and the reasons for families to discontinue irrigated farming. Finally, Section 4 covers the discussion and conclusions.

2. Materials and methods

2.1. Area description

The study area is located within Gwanda and Beitbridge districts in Matabeleland South Province in Zimbabwe at an elevation range of 500 − 700 m (Lowveld) (Fig. 1). Dryland farming and livestock herding are the prevailing livelihood activities in these communal lands. Rainfed agriculture is predominantly maize, combined with groundnuts, sorghum, millet and some vegetables. Four forms of smallholder irrigated agriculture are present in the area: communal irrigation schemes (collectively operated with interventions by external agencies), private irrigated farms (single families), community gardens (collectively operated small garden supported by NGOs), and very small home gardens for vegetable production ($<$ 0.1 ha). Six communal irrigation schemes were established in the 1960s, and produce maize, groundnuts and limited cash crops in the rainy season, and wheat in the cooler dry season. They abstract water from the Tuli and Shashe sand rivers with pumps supplied by the national electricity grid or a local solar grid. Although the total command area of the six schemes together is 423 ha, only 140 ha was under actual irrigation. Two schemes were non-functional, and the other four were under rehabilitation and operated between 17–55 % of their command area.

Both the Shashe and Tuli rivers form so-called sand river aquifers, which are unconfined alluvial groundwater systems consisting of sandy deposits in river beds of seasonal rivers in arid and semi-arid regions in sub-Saharan Africa (Duker et al., 2020). These natural storage systems are fully recharged annually when the river discharges after few rainfall events. Saturation of the sand layer occurs quickly after the river is submerged with floodwater (Mpala et al., 2020). Fig. 1 shows a map of the study area as positioned within the Mzingwane catchment. The Shashe and Tuli rivers merge to later flow into the Limpopo River, forming the border between Zimbabwe and South Africa.

The area is characterised by a single rainy season from November till March. Analysis of satellite-derived daily precipitation data for 2009–2019, shows that annual rainfall averages 339 mm (CHIRPS, 2019). Fig. 2 presents the total seasonal precipitation (July-June) and monthly totals for the main rain-fed cropping season (November-February). Inter- and intra-seasonal variabilities are high.

In addition, analysis of daily precipitation data shows that each month in the rain-fed cropping season (November-February) is characterised with on average one dry-spell of ten or more days, each with an average duration of 18 days. Although influenced by multiple

[1] Private smallholder irrigation is regarded as a form of farmer-led irrigation. However, in this study the term farmer-led irrigation is not used as it also includes groups of farmers and this study is focused on individual farming families.

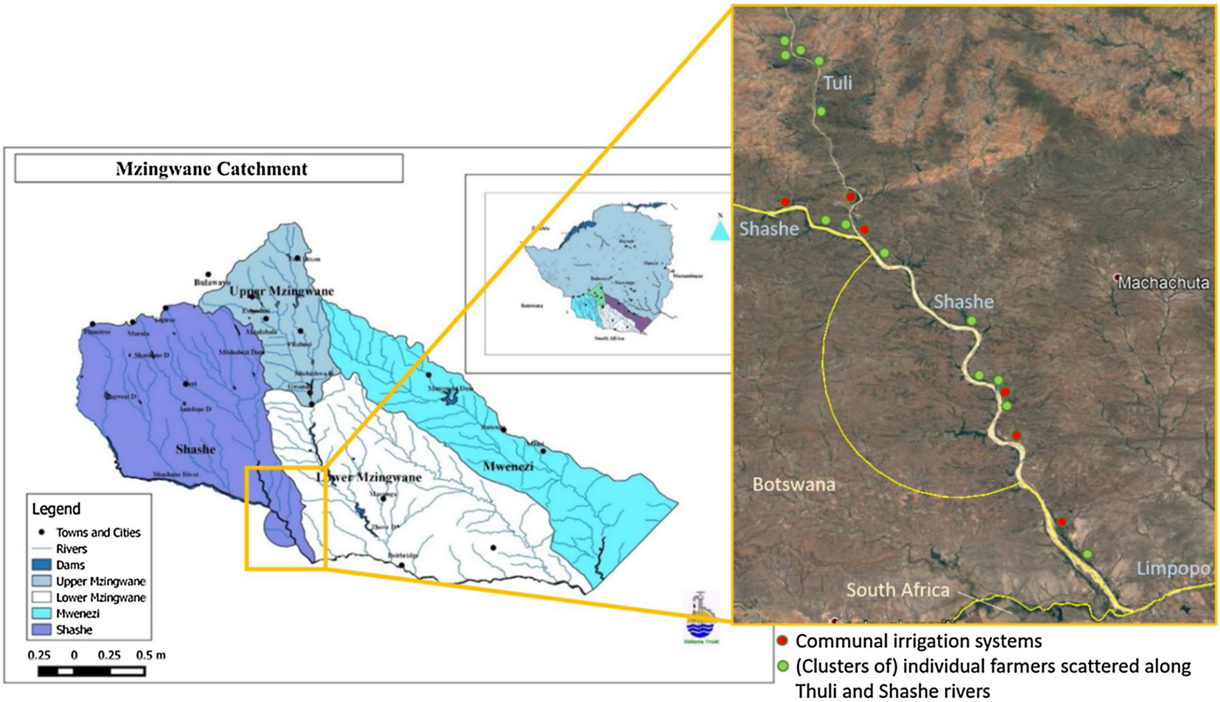

Fig. 1. Map of the study area in the Mzingwane catchment (source: adapted from Dabane, 2016; Google Earth, 2019).

Season	Seasonal precipitation (mm/year)	Monthly precipitation (mm/month)			
		Nov.	Dec.	Jan.	Feb.
2009/10	291	81	55	53	18
2010/11	359	57	120	139	0
2011/12	271	58	96	43	30
2012/13	298	39	29	153	10
2013/14	372	71	70	74	26
2014/15	310	52	131	13	35
2015/16	289	45	35	40	43
2016/17	567	71	197	139	89
2017/18	382	72	25	32	148
2018/19	250	31	70	33	73
Mean	*339*	*58*	*83*	*72*	*47*
SD	*87*	*15*	*52*	*49*	*42*
CV	*26%*	*26%*	*62%*	*69%*	*90%*

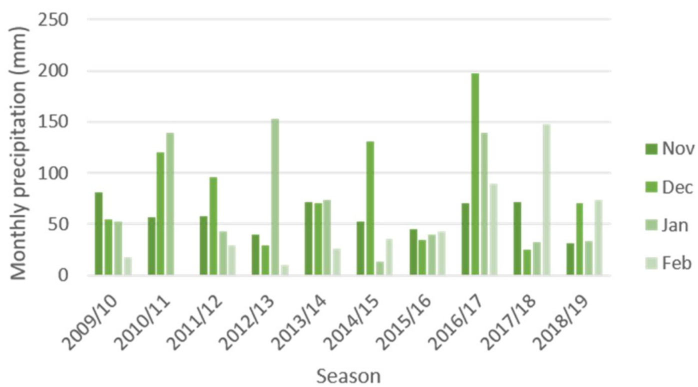

Fig. 2. Variability of seasonal and monthly precipitation in the cropping season, based on daily data retrieved from CHIRPS, 2019.

factors, a dry-spell of ten days is likely to have detrimental effects on rain-fed grain yields. The observed combination of unreliable rainfall quantities and recurrent dry-spells make rain-fed agriculture a very unstable source of livelihood. Furthermore, the study area is identified as one of the more severe drought-prone areas of the country with respect to future climate change (Brazier, 2017).

2.2. Conceptual framework

This study perceives private smallholder irrigation as a dynamic system, which is the outcome of interactions between technology, ecology and society. Therefore a Social-Ecological System (SES) approach is chosen, in which each of these elements and their interactions are analysed. In contrast to mere engineering systems, SES are characterised as self-organising, not fully controllable, and challenged by many uncertainties (Anderies et al., 2004). SES can be defined as '*an ecological system intricately linked with and affected by one or more social systems*' (Anderies et al., 2004). Through this conceptualisation the research aims to analyse the development of private farms within their wider dynamic socioeconomic and biophysical environment. Moreover, this approach enables those interactions that can fail and make the SES falter to be identified. The framework by Anderies et al. (2004) is based on the resource, users, infrastructure, and infrastructure providers. It is adapted in such a way that it visualises different spatial levels that relate to a degree of interaction with the farming family (Fig. 3).

Three main system levels are identified. At the centre is the irrigated farm that includes land (usually one plot, and in one case two plots), crops, water and irrigation technology. Fields are used by a single family and are not shared among multiple households. The farm is intertwined with the household (including labour, livestock and off-farm income) (blue arrows 7–8). Both elements are positioned within a local system that includes the local biophysical system (sand river aquifer), the local economy (local markets for selling crops and accessing inputs and capital), and the families' networks (inter- and intracommunity access to knowledge and capital). The interactions between farming families and the local level, the yellow arrows (4–6), are bidirectional. Finally, the outer system level refers to the macro-economy, climate and weather patterns, and national agricultural policies (primarily relating to collective irrigation schemes). While farming families are directly or indirectly affected by occurrences at macro level, they cannot directly influence these, and hence the red arrows (1–3) are one-directional. The different system components and their interactions are

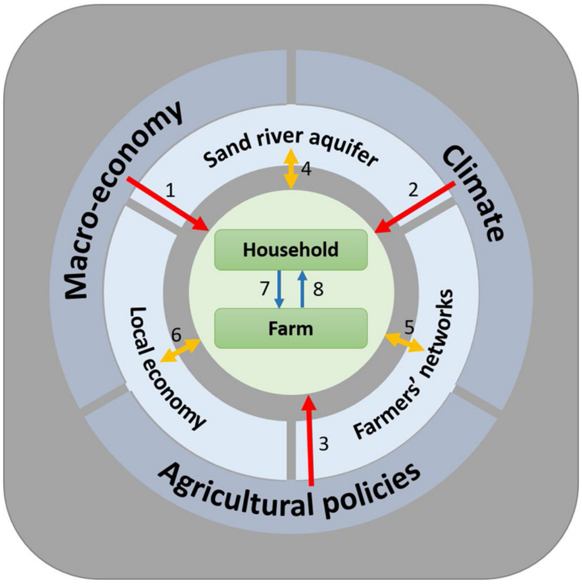

Fig. 3. Conceptualisation of private smallholder irrigation using sand river aquifers as a social-ecological system.

further described in Section 3.

2.3. Research methods

The study applied two methodological approaches: a farm inventory based on satellite images, and both quantitative and qualitative field work. Satellite images (Google Earth) from 2006 till 2019 were analysed to identify farm plots along the Shashe and Tuli rivers in southern Zimbabwe. Plots were selected within 200 m from the river beds as irrigation is assumed to be limited to this distance because of pumping power. The advantages of using satellite imagery include analysing time series, and hence identifying farmers who started or discontinued irrigation over time. Groundtruthing was carried out to assess irrigation operations and delineation, which resulted in a set of 108 farms, categorised according to operation (emerging, operational and discontinued) and use (rain-fed or irrigated). The farms categorised as 'irrigated' were further assessed through quantitative and qualitative fieldwork. A survey was held among 26 farmers to assess their water abstraction and irrigation technologies, crops cultivated, and marketing channels. This sample included 24 active irrigators and 2 two irrigators who discontinued, corresponding to 89 % and 11 % of the total number of identified operational and discontinued irrigated farms respectively.

Subsequently, 23 farmers were selected for semi-structured in-depth interviews and visual data collection (photography series and farm plot mapping), to evaluate irrigation operations, challenges and coping strategies, and household characteristics (Table 1). In order to understand the process and reasons to cease operations, additional families were searched for who stopped irrigating (six in total). Likewise, two farmers were interviewed who never managed to actually start irrigating, although they acquired a plot. A maximum variety purposive sampling method was used to seek variety in irrigation operations, challenges and coping strategies (Silverman, 2004). Selection criteria included the relative importance of farming for their livelihood, marketing strategies, abstraction and irrigation technologies, and plot location. In addition, semi-structured interviews and group discussions with farmers irrigating in six communal irrigation schemes were carried out (Table 1). Semi-structured interviews were held with other key actors, such as fuel traders, a mechanic, extension officers, and an NGO (Table 1). Market prices for crops, fuel, irrigation technology and commodities were gathered in several rural locations (farmers, shops, street markets, black market) and two towns (Gwanda and Bulawayo).

Table 1
Semi-structured interviews carried out.

Actor	Specifications	Interviews
Individual irrigating farming families	Operational	12
	In establishment	3
	Never started irrigation	2
	Stopped irrigating	6
	Total	***23***
Farmers in collective irrigation schemes	Farmer interviews	15
	Farmer group discussions	2 (7 + 16 farmers)
	Pump and solar grid operators	3
	Total	***20***
Other stakeholders	Mechanics and/or fuel traders	2
	NGO officers	3
	Extension officer	5
	Officer department of irrigation	1
	Total	***7***

3. Results

This section sets out the main findings of this research following the conceptualisation of the SES. First, the distinct characteristics of private smallholder irrigation are explained, together with the position of the farms within the household. Then, the emergence of this form of irrigated agriculture is clarified within the context of multiple crises: climate, faltering collective irrigation systems and economy. Subsequently, the challenges that farming families face in sustaining and expanding the farm, and their adaptive capacity, are described. Finally, the reasons for farms to cease are explained.

3.1. Characteristics of private smallholder irrigated farms along sand river aquifers

3.1.1. The irrigated farm: land, water, farming technology and crops

Private irrigation along the Tuli and Shashe rivers is characterised as smallholder family farming. They operate both irrigated and dryland farming on small fields close to the river banks. Individual access to land in these so-called communal areas is obtained through approval by local authorities. Land tenure is generally perceived as sufficiently secure to make investments in irrigation infrastructure. The total area of all the farms that were operational in the dry season of 2019 amounts to 44 ha, of which 31 ha covered irrigated farms (Table 2). The average area of an irrigated farm equals 1.1 ha.

Although the average plot size is 1.1 ha, the actual irrigated area averages 0.2 ha only, ranging from < 0.1 – 0.7 ha (Fig. 4). The majority (69 %) of surveyed farmers irrigate up to 0.25 ha. The farm plots are cropped both in the wet and dry seasons, and vegetables, staple, fodder, and fruit trees are combined. In the dry season, all farmers grow vegetables and fruits (tomatoes, kale, watermelon, butternut and many more), 31 % produce staple crops (maize, wheat), 23 % grow fodder crops (velvet beans), and 23 % have perennial fruit trees (bananas, papayas, and citrus). All families produce cash-generating crops, which diverges from more traditional staple crops in communal schemes or dryland farming. About half of the farms grow vegetables on the largest share of their plot, whereas 15 % concentrate on fodder (contract

Table 2
Total and average area of operational farms in the dry season of 2019.

	Irrigated	Rain-fed	Unknown	Total
Total area of operational farms (ha)	30.8	10.5	3.0	44.3
Number of operational farms	27	7	8	42
Average area per farm (ha)	1.1	1.5	0.4	1.1

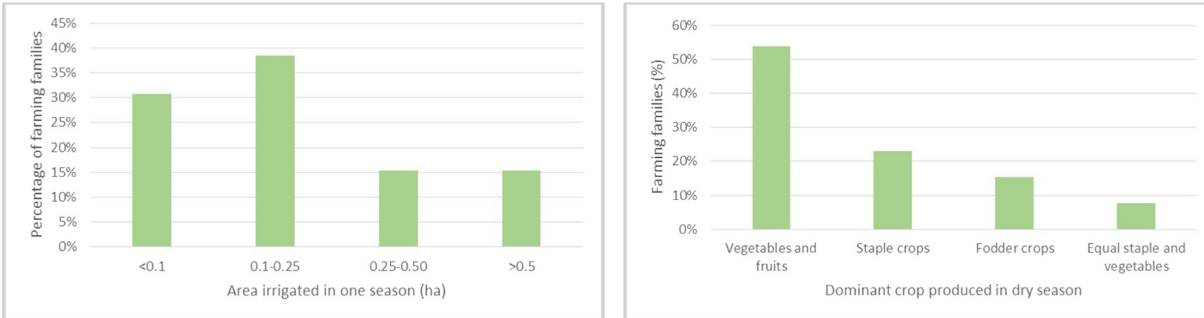

Fig. 4. Irrigated area per farm (left), and major share of crop type per farm in terms of area (right) in the dry season 2019.

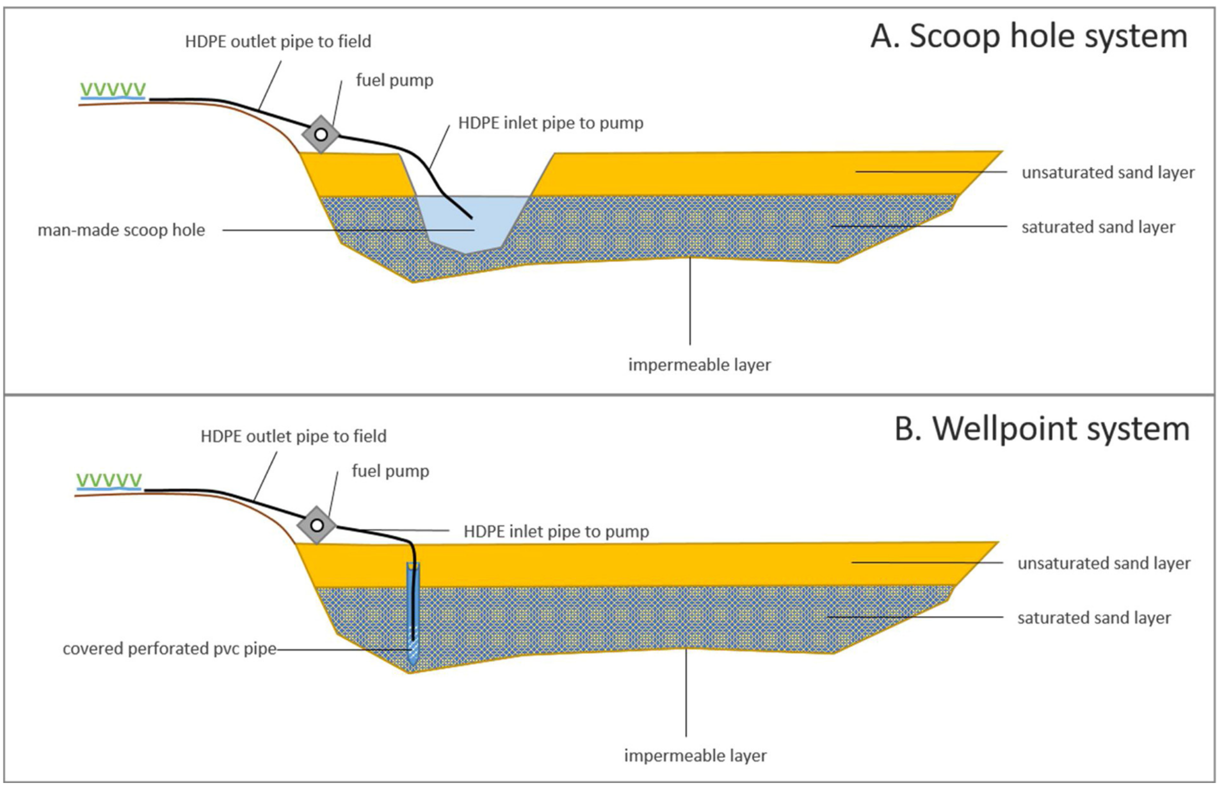

Fig. 5. Scoop hole (top) and wellpoint (bottom) abstraction systems found in the Tuli and Shashe sand river aquifers.

farming) (Fig. 4). Nevertheless, the area irrigated fluctuates substantially throughout the year, mainly depending on fuel access and marketing opportunities (see further Section 3.3).

The private irrigators abstract irrigation water from the sand river aquifers (arrow 4 in Fig. 3). They access water via large scoop holes (38 %), which are primarily used along the Tuli, and wellpoints (50 %), which can mainly be found along the Shashe (Fig. 5). Few farmers (8%) take water from surface water in tributaries or from a shallow well within their farm plot, assumed to be linked to the alluvium. Water levels are found between approx. 30 – 100 cm below the sand surface, depending on the location and season. Farmers invest and install the abstraction systems themselves within a few hours with limited technical aid. The scoop hole is manually dug and sometimes it is required to dig a new one closer to the main stream in the riverbed once the dry season progresses and water levels drop. The wellpoints are made with a method called 'simple sludge' whereby two PVC pipes are used with a manual vacuum technique to dispose sand and water. Abstraction locations are chosen to minimise pumping efforts. Hence, several farmers installed 2 or 3 wellpoints, each serving a different section of the field.

The majority of farmers (88 %) own Chinese manufactured fuel-engined pumps. Others (12 %) don't use a pump, but fill buckets to water their crops. The fuel pumps have a maximum discharge ranging from 30 – 60 m^3/h and a maximum head ranging from 20 – 30 m. Most are run with petrol (94 %), and few with more efficient, and hence preferred but more expensive, diesel (6%). About two-thirds of the families purchased a new pump, while one third acquired a second-hand pump. They are bought from funds obtained through selling livestock, sometimes directly from South Africa and to a lesser extent Botswana, and mostly through local networks and the lively trade in the border region (arrow 5 in Fig. 3). Prices of new petrol pumps bought from South Africa or Botswana, as reported by the farmers, all fall in the range of USD200-300, which is equivalent to approximately 10 goats or 1 cow. Second-hand pumps are cheaper, approximately 3 goats. Prices for new pumps in nearby towns (Gwanda or Bulawayo) are higher and range from USD490-760 (reflecting the black market exchange rate that is most commonly applied at the time of research). Irrigation application methods include hosepipes (88 %), buckets (12 %), and sprinklers (8%). Few farmers combine different irrigation methods, e.g. hosepipe and sprinklers, to balance fuel costs. The price of 100 m of HDPE pipe with a diameter of 40 – 63 mm varies from USD80-180.

Table 3
Home consumption and marketing of irrigated crops (n = 26).

Use of produce	Home consumption	96 %
(*non-cumulative*)	Sold locally	81 %
	Sold locally schools/clinics	19 %
	Sold town markets	4%
	Sold to traders	8%
	Contract farming	8%
	Home consumption only	12 %
Largest share of produce	Home consumption	54 %
	Sold	38 %
	Equal home consumption and sold	8%

Table 4
Private smallholder farm dynamics along the Shashe and Tuli rivers (based on assessment dry season 2019).

	Irrigated	Rain-fed	Unknown	Total
Existing in 2006:	1	15	14	30
Operational	–	6	1	7
No more in use	1	9	13	23
Emerged 2006 – 2019:	**45**	**14**	**16**	**75**
Operational	27	1	7	35
No more in use	18	13	9	40
Under establishment in 2019	**3**	**–**	**–**	**3**
Total	**49**	**29**	**30**	**108**

3.1.2. The farm within the household: labour, livestock, benefits and off-farm income

Interactions between the farm and the household are represented by arrows 7 and 8 (Fig. 3). The household provides labour and capital to run the farm. Labour is not straightforward, as the farms are located at an average distance of 6 km from the homesteads. Very few families live next to their field and can hence monitor their crops and equipment relatively easily, and 65 % have therefore built a temporary shelter on their farms. Labour is provided by several family members, though mostly male dominated. Very few families hire permanent labour.

For about half of the families the irrigated plot is the main source of livelihood. They derive benefits in food, fodder and income through home consumption (96 % of the families) and local sales (81 %), while only few families have been engaged in some type of marketing contracts and explore selling produce beyond the local community to advance income levels (Table 3). Poor access to infrastructure and information, combined with a strong will to operate independently, are the major reasons that for over half of the families, home consumption forms the primary destination of the harvest (see further Section 3.3).

Most families (62 %) have diversified livelihood sources, such as producing local artefacts and crafts, seasonal jobs, irrigated farming in collective schemes, livestock trade, or a pension. About half of the farming households receive remittances from family members, mainly in South Africa. Nevertheless, 31 % of the irrigating families don't receive any income from off-farm employment or remittances. A majority of families herd livestock; 77 % own goats and 54 % have cows, which is similar to average rural homes in Zimbabwe (FAO, 2019). Larger investments such as irrigation pumps, are made through livestock trade. Short-term operational costs, like energy and inputs, are usually paid from crop sales or other income sources, and selling livestock is not a preferred option.

The irrigated farm is thus of substantial importance within diversified livelihood strategies, which is also demonstrated by the fact that most families construct a temporary shelter at the farm, travel long distances to the plot, or to a minor extent, hire permanent labour. Most families have plans for future investments, e.g. expanding the farm or moving their homes to the river. As a result of establishing an irrigated farm, the majority of farmers abandon or minimise the use of their family rain-fed plot. They lack sufficient labour to produce on both, and the latter is regarded less beneficial and reliable due to erratic rainfall patterns.

3.2. Emergence of private smallholder irrigation

Analysis of satellite images indicates a growth in the number of private irrigated farms over the past years. Thirty private smallholder farms existed in 2006, while an additional 75 have emerged between 2006 and 2019. Of these 75 new farms, at least 60 % were irrigated (Table 4). The remaining 40 % of new farms were either rain-fed or it is not known. Of all irrigated farms that emerged between 2006 and 2019, 60 % was operational, while 40 % was not in use at the time of the field surveys (dry season 2019). Another three farms were in different stages of establishment. The irrigators have on average been in operation for five years, ranging from 1 to 13 years. The farms that have been identified as 'no more in use' include those where families stopped irrigation, and those for which the plan to irrigate never materialised (see further Sections 3.3 and 3.4).

The emergence of private smallholder irrigation along sand rivers is explained by three drivers: droughts and unreliable rainfall, failing communal schemes, and economic catastrophe (arrows 1–3 in Fig. 3). First, several families experience the results of severe droughts and dry-spells, which make dry-land farming unproductive, and home gardens irrigated from shallow groundwater wells less beneficial as water tables decline. As a result, they establish new farms along the rivers, up to 20 km from their homes. The abundance of water in the sand entices families to the river banks to produce crops, herd livestock and some to build a new home. The burden of moving and clearing new land thus outweighs the increased labour and pumping costs associated with deepening wells at their homesteads. Water availability in the sand rivers thus forms a catalyst for private smallholder irrigation development.

Other families start private farms because they lost confidence in the operations of collective irrigation schemes. These fail to provide a secure livelihood source because of an endless cycle of collapse and recovery from infrastructure deterioration, faltering energy supply, politicised top-down agricultural programmes, and poor or absent marketing strategies. Six communal irrigation schemes are present in the area, which have been developed pre-independence in the 1960s, with original investments made by, and strong reliance on the colonial and minority-rule governments. More recently, they have been intermittently engaged in rehabilitation and modernisation programmes, and have now moved from using diesel to local solar or national electricity grids. Despite these rehabilitation programmes and the establishment of farmer irrigation management committees, the schemes remain strongly dependent on external agencies and produce sub-optimal yields. For example, several government plans were introduced in the last decades that forced farmers into unfavourable contract farming, as similarly experienced in other irrigation schemes in the country (Zawe, 2006). The recent command agriculture programme was a final push out of the schemes for several families. Farmers were forced to produce maize and wheat based on contracts that left them indebted. Low profitability combined with continuous discussions and problems among farmers are major reasons for those farmers who can afford it, to opt for a more independent form of irrigated agriculture in which they can take decisions on what, when, and how to grow, and where to sell. These first two trends indicate that individual farming families have an agricultural background. Half of the families have experience in irrigation before establishing a private farm, while 38 % have worked in rain-fed agriculture only.

The third encountered driver for many families to establish an irrigated farm relates to economic instability and continuous crisis. These result in high unemployment, very high inflation and cost of living, and burdensome access to cash and commodities, which in turn contribute to rising levels of food insecurity in both rural and urban areas (United

States Department of State, 2019). By engaging in private irrigated farming, families aim to better provide for family and livestock.

Although the drivers to invest in a farm along the sand rivers may be different, all families aim to be independent and follow an adaptive approach in the establishment and pursued expansion of the farm: starting with a limited cropped area, testing the field with rain-fed crops, using borrowed or second-hand technology, sharing equipment, or spreading risks by not immediately giving up existing livelihood sources. Livestock and access to off-farm income are therefore essential in developing the farm, and in absorbing shocks.

3.3. Adapting to a harsh environment

In social-ecological systems, challenges can commence from biophysical and/or socioeconomic factors. For the development of private smallholder irrigation along the Shashe and Tuli rivers the challenges are manifold. But contrary to numerous irrigation activities in sub-Saharan Africa, the water resource itself, in terms of water availability, is posing no direct challenges to the operations of farming families (arrows 2 and 4 in Fig. 3). Despite being located in the driest part of Zimbabwe, the water in the alluvium remains abundant throughout the dry season, and none of the farmers have ever experienced water shortages in the sand river aquifers, even in recent dry years. As one of the farmers mentioned that people suffered crop losses in many parts of the country during recent droughts, whereas the water in the Shashe remained plentiful with water levels not dropping to levels that farmers could not access.

Farmers face minor challenges with other biophysical issues. Soil fertility is not mentioned as a concern, and the large majority of farmers (92 %) apply manure and chemical fertilisers. Farmers reported challenges with poor fencing and crop damage due to roaming livestock, and to a limited extent with pests. Infrastructural failure occurs as the use of poor quality fuel, the sandy environment, and untimely application of oil, cause pump breakdowns. Although farmers and mechanics are in general well able to maintain equipment, technical defects occasionally lead to crop losses.

The major issues that constrain farmers' operations are socioeconomic in nature, and originate from the macro-economy and the local economy (arrows 1 and 6 in Fig. 3). As a response, farmers employ coping strategies at the farm plot and the household that are facilitated through interactions with the local economy and farmers' networks (arrows 5 and 6 in Fig. 3). Paramount is the economic crisis that has been hitting Zimbabwe for the past two decades, with just few periods of minor recuperation. More recently, after the re-introduction of a Zimbabwean currency in 2017 and the abolishment of the multi-currency system in 2019, annual inflation has risen sharply, officially reported 176 % in June 2019 (ZimStat., 2019), and reaching 300 % two months later (International Monetary Fund, 2019). Real GDP growth rate equals -8.3 % in 2019 (International Monetary Fund, 2019). Food prices have risen accordingly, and fuel has become a scarce commodity. At the few fuel stations where there is availability, access is restricted to vehicles. Since farmers are strongly depending on petrol or diesel, energy access is one of their major struggles in sustaining and expanding their farm. Consequently, there is a lively trade in fuel by local transport operators and smugglers from nearby Botswana and South Africa, who provide petrol at fluctuating prices (USD0.90-1.90/l), and of variable quality. At the same time, barter trade of agricultural produce has increased as a response to the economic situation, which consequently worsens farmers' ability to buy fuel as fuel can only be bought with cash. Planning crop production is hence largely steered by fuel availability. One way to adapt is producing fast-growing crops that can be harvested continuously to generate a continuous modest cash flow. In addition, farmers apply energy-saving strategies, like longitudinal fields along the river with multiple abstraction points, early planting to avoid peak irrigation demands in the hottest months, or reduction of the cropped area. Selling livestock to purchase fuel is regarded a last resort. Despite the creative ways of adapting to energy deficits, many farmers struggle in maintaining a secure production level. As a result, harvests and related income fluctuate over time. Although solar-powered irrigation would address fuel-dependency, this technology is basically absent along sand rivers due to the high initial investment costs as compared to fuel pumps.

Another socioeconomic limitation to private smallholder irrigation development is poor access to markets (arrows 1, 5 and 6 in Fig. 3), coupled with the faltering economy. Only few farmers have temporarily experimented with formal marketing strategies such as contract farming with supermarkets or seed companies. Critical impediments are lack of transport, limited knowledge about opportunities and market price differentiation, competition from cheap imports from South Africa, and too little and uncertain production. Finally, inadequate fuel access hinders coordinated planning of crops among farmers, which is needed to collectively organise access to markets.

Farmers' networks are key in developing and sustaining their farm endeavours. The majority of farmers are positioned in clusters of several farms through which they exchange knowledge on agronomics and equipment, sometimes share fuel or technology in urgent need, and few collaborate in local marketing. For example, initially only a handful of farmers possessed the skills to install wellpoints, and charged an installation fee to others. Later they taught other farmers how to manually drill the wellpoints. Others benefit from contacts through communal irrigation systems, for example with extension officers and NGOs linking them with contracting companies, which exposes them to new crop varieties or agronomic skills. On the other hand, some of those who lack previous irrigation experience make other strategic choices to make up for this disadvantage by actively gaining knowledge and skills through working closely with other irrigators or by temporarily working in a community garden or collective scheme. Some farmers apply skills gained from previous jobs (e.g. mechanic), or are more experimental and risk-taking in nature, which enables them to accustom new pumping and irrigation combinations, test new types of pest control, or explore alternative marketing channels. Most irrigating farmers partially access inputs (seeds, fertilisers) from non-irrigating community members as part of annual governmental food aid provisions. Private farms thus do not operate and develop in isolation but are embedded in adaptive rural livelihood strategies and social networks.

3.4. Discontinuation of private smallholder irrigation

Despite diverse modes of adapting to changing circumstances, not all families manage to maintain production. A minority of farming families (15 %) ceased operations temporarily (maximum 1 season) due to technical or health problems. Moreover, 40 % of all identified irrigated plots have been non-operational for a longer time (Table 4). There are three main explanations for this. First, some families intend to irrigate their farm but don't manage to become operational as the required level of investment is not within reach. For example, because they acquired land and were able to invest in a pump, but lack pipes to irrigate. Second, a majority of the fallow lands were once irrigated but farmers discontinued because they could not cope with shocks. Balancing cash flows and energy in an economically volatile environment proves to be too arduous, and farmers drop out. Families who don't have alternative income sources (31 %) struggle the most in maintaining the farm. Although farmers stop irrigating, none of them actually dispose the irrigation equipment or their land, which shows their eagerness to restart once new opportunities may arise. Finally, several families, primarily the male heads of households, find more promising employment in South Africa. Some completely stop farming, while others try to manage it remotely, or hand it over to others. These latter outsourcing options do not seem to be long-lived. The region is distinctly migratory, which thus serves both as a facilitator to (inputs, technology and cash) and as an escape route from private smallholder irrigation.

4. Discussion and conclusions

4.1. Discussion

Individualisation of irrigated agriculture is an observed trend along ephemeral sand rivers in southern arid Zimbabwe. Based on a strong desire to operate independently, families establish private farms to produce vegetable, staple and fodder crops. These private smallholder ventures are distinct from most other documented forms of private irrigation. First, it is characterised by a context-specific and critical interplay of a unique water resource, technology, and energy. The ephemeral sand rivers provide a secure annually recharged source of water as opposed to conventional groundwater resources or rainfall. Yet, access for productive agriculture requires a significant investment in technology and mobilisation of energy in a fuel-deficient environment. Second, the drivers for establishing a private farm diverge from other documented cases in SSA, which mostly arise in areas with strong or new markets where entrepreneurial farmers take advantage of. These regions where large numbers of private irrigators benefit employ a variety of context-specific irrigation technologies and water resources to grow cash crops, can be regarded as 'irrigation hot spots[2] '. For example, market-oriented farmers, often young, manage to gain considerable profits from the production of tomatoes in Ghana (Ofosu et al., 2010), onions in Burkina Faso (de Fraiture and Giordano, 2014), and vegetables in Kenya (Bosma, 2015). These booming hot spots mostly arise in the vicinity of or are well connected to urban markets (Colenbrander and van Koppen, 2013; Danso et al., 2014). As opposed to this opportunity-driven form of private smallholder irrigation, there is an absence of strong markets along the Shashe and Tuli rivers in Zimbabwe. Instead, families commence an irrigated farm out of a certain crisis: recurrent droughts and dry spells, failing collective irrigation, and persistent economic malfunction. Hence, in this case there is no such thing as an irrigation hot spot, rather irrigation as a fall back option.

As a result of these features, there is just a subtle line between failure and success in private smallholder irrigation along sand rivers, and it hardly ever exceeds the level of subsistence income. It is challenging for families to embark (necessity to invest in infrastructure), and to endure and expand (access to fuel and markets). Some families do not manage to make the farms operational or cease business because they migrate or have reached the limit of their adaptive capacity. Nonetheless, though investing within this harsh environment is risky by default, several families succeed in developing adaptive strategies that are specific to this border-region. For them, off-farm income, remittances, previous experience, gradual expansion of the farm, and local networks are vital to absorb economic shocks, as is also mentioned as one of the characteristics of private and farmer-led irrigation (Woodhouse et al., 2017). They continuously weigh serving short-term subsistence needs and long-term performance, as is found in other developing regions (Smucker and Wisner, 2008). As a response to shocks, irrigators thus reduce their vulnerability (adjust farm operations to volatile energy access) and increase their adaptive capacity (enhance networks to access labour, skills and knowledge). Both components, plus the fact that they are effective in exploiting the advantages intrinsic to their surroundings (vicinity of international borders and a stable and reliable water supply), enhance the resilience of private smallholder irrigation along sand rivers. Hence, these families succeed in deriving a significant contribution from irrigated agriculture to their livelihood. The relevance of the farm income is also demonstrated by the investments made in cash and labour, and the willingness to expand. Still, these families are far from the more commercial cash-generating private irrigation as found in other African cases (Ofosu et al., 2010; de Fraiture and Giordano, 2014; Woodhouse et al., 2017).

The conceptualisation of private smallholder irrigation as SES, has contributed to understanding the different system components that influence these farms. The interactions among these elements at different spatial levels, including the drivers for private smallholder development, were delineated. As such, it supports the identification of challenges that emerge from different system components, which gives direction for potential interventions. However, the approach is limited in elucidating temporal dynamics and in differentiating the heterogeneous character of rural families. Alternative approaches could be suitable in analysing the processes that mold private smallholder irrigation over time. For example, alternate system regimes of farming households (Tittonell, 2014), or archetype approaches to rural development (Sietz et al., 2019), could be appropriate avenues to assess the diverse pathways and thresholds for emergence and expansion of private smallholder irrigation.

4.2. Conclusions

This study in southern Zimbabwe contributes to the diversity of documented private smallholder irrigation in sub-Saharan Africa. It concurs with the notion that this specific form of irrigated agriculture comprises of a spectrum that ranges from subsistence to more commercial individual farms (Wiggins and Lankford, 2019). By particularly researching failure and the challenging context in which private smallholder irrigation arises along sand rivers, new insights are generated regarding the limits to the much praised adaptive capacity of private irrigation. This case demonstrates that these limits are stipulated by the nature of the water resource, the harsh economic environment and the absence of market linkages, which leads to farming families being 'adrift' and not able to join the 'shift' towards prosperous private irrigation ventures. For these struggling families, the required investments in the necessary pumping technology or adjusting to socioeconomic impediments could not be realised. The new farms are crisis-driven without a strong market orientation, and as a result they contribute mostly to subsistence income with minimal exposure to regional markets. Those more successful families have thus managed to neutralise the climatic shocks they have been exposed to as a result of the favourable water availability in the shallow sand river aquifers. Also, there are certain conditions that are conducive to coping with socioeconomic obstacles (knowledge, skills, capital, networks, and remittances/off-farm income). Yet, sustaining irrigation ventures in this harsh climatic, economic and political environment, and adapting to changing circumstances in both the short and long term remains a major challenge.

Understanding the heterogeneity of private smallholder irrigation in SSA in terms of emergence, development and failure, is crucial in contributing to the complex issue of mobilising potential support by private, governmental or non-governmental agencies. This Zimbabwean case illustrates that current constraints for private smallholder irrigation development along sand rivers emanate from economic volatility, rather than from water scarcity and climatic uncertainties. Therefore, farming families could potentially benefit from investments for enhancing markets and accessing finance for alternative (solar) pumping technologies (Duker et al., 2020). To overcome the higher investment costs, establishing attractive financial mechanisms to support farmers in experiments and trials could be a sensible approach to catalyse innovations to overcome these context-specific impediments to growth (van der Zaag, 2010). These measures would require a paradigm shift in national irrigation policies and a redistribution of financial resources available for support programmes. However, the desirability of external support is disputable since the strength of private smallholder irrigation is related to the substantial level of farmers

[2] The term hot spot is applied in different scientific fields such as biodiversity research (Myers et al., 2000) and biogeochemical studies (McClain et al., 2003), where it is defined as an area with an exceptional occurrence of a certain endemic species (although with habitat loss) or chemical reactions as compared to its surroundings.

own investments, which result in a strong sense of ownership and adaptive capacity. There is a risk, if not undertaken conscientiously, that external interventions impair these properties and lead to a vicious dependency cycle as observed with many irrigation systems. Any potential future interventions therefore need to do justice to the independent way of operating by smallholder farming families.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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