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205

Working Paper

Environmental Flows in Support of Sustainable Intensification of Agriculture in the Letaba River Basin, South Africa

Chris Dickens, Cory Whitney, Eike Luedeling, Vuyisile Dlamini, Gordon O'Brien and Ikhothatseng Jacob Greffiths

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International Water Management Institute (IWMI)
P. O. Box 2075, Colombo, Sri Lanka

The authors:
Chris Dickens is a Project Leader and Principal Researcher at the International Water Management Institute (IWMI), Colombo, Sri Lanka; Cory Whitney is a Postdoctoral Researcher at Horticultural Sciences, Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Germany; Eike Luedeling is a Professor at Horticultural Sciences, INRES, University of Bonn, Germany; Vuyisile Dlamini is a Researcher with Rivers of Life Aquatic Health Services, University of Mpumalanga, South Africa. She conducted the survey of agricultural practices for this study; Gordon O'Brien is a Senior Lecturer at the School of Biology and Environmental Sciences, University of Mpumalanga, South Africa. He is an environmental flow specialist who contributed environmental flow data for this study; and Ikhothatseng Jacob Greffiths was a Research Officer – Agricultural Economics at IWMI, Pretoria, South Africa, at the time this study was conducted. He supported the survey of agricultural practices for this study.

Dickens, C.; Whitney, C.; Luedeling, E.; Dlamini, V.; O'Brien, G.; Greffiths, I. J. 2023. *Environmental flows in support of sustainable intensification of agriculture in the Letaba River Basin, South Africa*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 51p. (IWMI Working Paper 205). doi: https://doi.org/10.5337/2022.226

/ environmental flows / sustainable agriculture / sustainable intensification / small-scale farming / livelihoods / river basins / water resources / water management / water availability / water demand / irrigation water / irrigated farming / subsistence farming / crop water use / water requirements / crop yield / ecosystem services / river flow / catchment areas / fishing / livestock / smallholders / farmers / gender / women / risk / rural communities / policies / food security / Sustainable Development Goals / water rights / land rights / modelling / South Africa /

ISSN 2012-5763
e-ISSN 2478-1134
ISBN 978-92-9090-947-7

Please send inquiries and comments to IWMI-Publications@cgiar.org

Acknowledgments

The authors would like to thank the respondents of the key informant interviews, who were farmers that benefited from river flows. Special thanks go to researchers who provided secondary data on hydrology, and to the United States Agency for International Development (USAID) for allowing us to use the data on environmental flow hydrology.

Project

This research was conducted under the CGIAR Research Program on Water, Land and Ecosystems (WLE) project titled Water and land management trajectories – best bet options for sustainable agricultural intensification, in particular outcome 5.1: Evidence, tools and decision support frameworks for sustainable agricultural landscapes.

Collaborators

International Water Management Institute (IWMI)

University of Bonn, Germany

Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Germany

University of Mpumalanga and Rivers of Life, South Africa

Donors

This research was carried out as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) and supported by Funders contributing to the CGIAR Trust Fund (https://www.cgiar.org/funders/).

Contents

Acronyms and Abbreviations

DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
E-Flow	Environmental Flow
EVPI	Expected Value of Perfect Information
Mm^3	Million Cubic Meters
NWA	National Water Act
PLS	Partial Least Squares
PTO	Permission to Occupy
SDG	Sustainable Development Goal
VIP	Variable Importance in Projection
VoI	Value of Information

Summary

The purpose of this paper is to analyze the relationship between achieving environmental flows, or e-flows, in the Letaba River in South Africa and the provision of water for sustainable small-scale agriculture adjacent to that river. The paper is divided into two parts: the first characterizes the livelihood and agricultural processes in communities along the Great Letaba River, and the second analyzes the risk to livelihoods, particularly those related to water availability for small-scale agriculture, while maintaining e-flows in the river.

Implementation of e-flows is now generally recognized as an essential part of water resources management. They are designed to ensure that sufficient water is retained in a river to protect river ecosystems and all the beneficiaries of services that arise from those ecosystems. Inevitably, there is a perceived conflict between the need to retain some water in the river and the needs of agriculture. Understanding the relationship between e-flows and the use of water for small-scale agriculture is important for the management of trade-offs.

The Letaba River Basin is located in the eastern part of the Limpopo province in South Africa. It is one of the most important river basins supporting the livelihoods of people living adjacent to the river. The Letaba River sustains many vulnerable human communities, who depend on the ecosystem services deriving directly from the river. This relationship is representative of the situation in the larger Limpopo River Basin, which supports an estimated 18 million people across the riparian states of Botswana, Mozambique, South Africa and Zimbabwe. The water resources of the Letaba River are heavily utilized due to expanding social and economic activities, and also because of the construction of instream dams. While minimum flow requirements to maintain the ecosystem (e-flows) have been established for the Letaba River by the Department of Water and Sanitation of the South African government, there is constant competition between anthropogenic needs for water, especially for small-scale agriculture, and water dedicated to sustaining key environmental processes as part of the e-flows. Explicit information pertaining to the extent of the dependency of these communities on e-flows carried by the Letaba River is lacking. In this study, we evaluate the socioecological consequences of the potential trade-offs between maintaining e-flows and providing water for sustainable subsistence agriculture and livelihoods to the vulnerable human communities living along the lower Great Letaba River.

The results from our study indicate that irrigation water demand from subsistence agriculture in the Great Letaba Basin amounted to around 2 million cubic meters annually with median demand not exceeding 300,000 cubic meters per month. This means that irrigation water demand from smallholder agriculture only amounts to about one-tenth of the estimated e-flow requirement. However, small-scale farmers have to contend with an increasing crop water gap which limits irrigated agriculture, especially during the dry season. Given the need to sustainably maintain e-flows for ecological purposes, crop water gaps are only likely to increase and compromise the sustainability of irrigated agriculture. With active upstream supplementation of river flows to maintain both environmental and livelihoods-oriented river flows, the crop water gap can be fully eliminated. This supplementation of river flows, which might be through dam releases, would improve irrigation water availability and have positive implications for the livelihoods of subsistence farmers, who would be able to cultivate crops all year round. For this scenario to be realistic, it depends on the availability of upstream water resources, which may entail restriction of the current uses of water further upstream, a scenario not evaluated in this paper.

The Letaba River was selected as a test case because of its accessibility to the research team, and the presence of suitable communities practising riparian agriculture. To achieve its objectives, this study blended the application of holistic modeling approaches together with small-scale farmers' water use requirements to generate conceptual impact pathways and quantitative models to reveal the relationships between e-flows and agriculture and to forecast decision outcomes.

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Introduction

Background

The regulators of water resource use in the Limpopo River Basin, which extends across Botswana, Zimbabwe, South Africa and Mozambique, have committed to sustainable water resource development (Malzbender and Earle 2009; Hughes et al. 2002). In South Africa, the National Water Act (NWA 1998) requires prioritization of water flows to meet the daily basic or domestic (drinking and personal sanitation) needs of people and the needs of the ecosystems (UN-Habitat and UNEP 2007). According to the NWA (Chapter 3, Part 3), it is important to ensure that a sufficient quantity, quality and duration of water flows, which vary according to a river system or water resource, are maintained for a river's ecological integrity and functions. One of the environmental flow, or e-flow, management principles of the NWA is that "human use of water does not individually or cumulatively compromise the long-term sustainability of aquatic and associated ecosystems." According to Winter (2009), by effectively managing South Africa's water resources through e-flow management principles, we can ensure that a sustainable supply of water is available for aquatic ecosystems (thus aligning with Arthington et al. 2018), and the basic human needs of the vulnerable human communities living in the basin. While the other riparian states of the Limpopo Basin do not have explicit requirements to establish and maintain e-flows for ecosystems and basic human needs, such mechanisms have been established in South Africa and the Limpopo Watercourse Commission (LIMCOM), a regional commission for the Limpopo Basin, to contribute to the protection of water resources in the context of sustainable development and use of water (Hughes et al. 2002).

Rural human communities, which include vulnerable communities located close to river systems, are typically reliant on water for their livelihoods. Water for subsistence agriculture and fisheries is one of the services that people derive directly from river systems in southern Africa. It helps to alleviate poverty and establish resilience in many rural communities. As a result, communities that live within easy access to a river system are likely to be affected by abnormal changes in water flows and the condition of a river's ecosystem. Many small farmers living along the Limpopo riverbank make use of the limited water resources available to them in what is a relatively arid region (UN-Habitat and UNEP 2007). The basin also has large-scale commercial farmers who contribute to the food security of the region. The Chokwe Irrigation Scheme, located just upstream of the Limpopo estuary and its associated floodplain, supplies water for irrigation to 9,000-13,000 hectares (ha) of agricultural land. The main or formal commercial water users of this scheme are regulated through governmental water-use authorizations and/or licenses. Small farmers, including subsistence farmers, are not generally required to obtain licenses to use water in the Limpopo Basin (Anderson et al. 2007; Ncube 2018). However, small-scale farmers who use water from rivers may require a general authorization that regulates collective use of water in an area. A general authorization may be issued to abstract or store surface water with the volume of water differing as per catchment. According to the 2016 revised general authorization, an annual maximum volume of 2,000 cubic meters (m^3) up to a maximum abstraction rate of 1 liter per second (l/s) at any time during the year is allowed per user in the Limpopo Basin. For groundwater, 40,000 m^3 per user per year are allowed by the general authorization for a property. Available storage of water in the lower Limpopo Basin is minimal; so, irrigation is dependent on river flows as well as some dam water releases. Rural stakeholders rely to a greater degree on immediate ecosystem service sources from the river and are most vulnerable when these flows are diverted elsewhere as they may not have the buffering comfort of water storage and financial well-being that may be the situation of larger farmers (Turpie et al. 2017).

The aim of this study is to evaluate the water requirements for subsistence agriculture by rural stakeholders who live in close proximity to the Great Letaba River, which serves as a proxy for the middle and lower Limpopo Basin. We evaluate these users' dependency on water and the dynamics of their water use. We relate their demands to e-flows from the Great Letaba River to consider the trade-offs involved in providing e-flows while at the same time meeting the subsistence agriculture needs of these vulnerable human communities.

Context of the Study

In many parts of the world, livelihoods in rural communities are linked to agriculture, which is mostly practised at a smallholder and subsistence level (Lemke et al. 2012). According to Querner et al. (2016), most of the agricultural production in sub-Saharan Africa takes place on subsistence farms. Our research project puts emphasis on small-scale agriculture by evaluating how changes in river flows may impact the sustainability of subsistence agriculture in the Letaba catchment in South Africa. For agricultural production systems to be sustainable, they should meet the requirements of biological productivity, economic viability and reduced levels of risk; they should be resilient and thus able to recover from stresses and shocks while not undermining the natural resource base (Lemke et al. 2012). Smallholder farmers have a role in the attainment of Sustainable Development Goals (SDGs) by countries, as food and agriculture are core to a number of these goals. Goal 2 of the SDGs aims to end hunger and malnutrition and to double agricultural productivity. Bertule et al. (2018) state that for agricultural production to be sustainable, the management and preservation of natural resources and biodiversity (SDG 15) is integral to small farm development. Smallholder agriculture will play a large role in the sustainable food systems of the future (Terlau et al. 2019). Therefore, understanding the extent, agricultural practices and socioeconomic needs of subsistence farming in a river catchment is crucial to meeting the SDGs.

The Limpopo River Basin supports over 18 million people in 5,200 human settlements (UN-Habitat and UNEP 2007; Petrie et al. 2014) across the riparian states of Botswana, Mozambique, South Africa and Zimbabwe. Of this population, CPWF (2014) reported that some 14 million live within the Limpopo River Basin and depend on the ecosystem services associated with river flows and the income generated from rainfed agriculture. According to LBPTC (2010), irrigated farming is the largest water user in the river basin, accounting for about 50% of the total water demand, followed by urban water supply which uses 30%, and mining, power generation and rural water supply, which together claim only 6%. Of the total estimated water present in the basin in 2010 (4,730 million cubic meters [Mm^3]/a), two-thirds were used by South Africa, with Zimbabwe using 30%, Mozambique 6% and Botswana 2%. Irrigated agriculture is a key economic sector in the Limpopo River Basin with large-scale and smallholder agricultural systems common in the catchment area (Kahinda et al. 2016). There are many small farmers and commercial farmers along the Limpopo River who make use of the limited water resources in the basin (UN-Habitat and UNEP 2007). The water demand for agriculture, mining, industries, community livelihoods and associated resources has increased over the years (UN-Habitat and UNEP 2007). LBPTC (2010) has projected that water demand for small irrigation will increase from 270 Mm^3/a to 1,200 Mm^3/a due to expansions in different parts of the basin.

The Great Letaba River is a tributary of the Olifants/Elephantes River of the Limpopo River System and is located in the central Limpopo Basin. Small-scale and commercial farmers rely on the river to irrigate their crops and for other ecosystem services. The Letaba River Basin is divided into the Klein Letaba, the Middle Letaba and the Great (or Groot) Letaba rivers. The main tributaries of the Letaba include the Nsama, Letsitele and Molototsi rivers, which originate in the mountainous areas to the west of the catchment. The Letaba River drains into the Olifants/Elephantes River near the Mozambican border, which then drains into the Limpopo River before reaching the Indian Ocean. Generally, the Letaba Basin experiences hot summers. Over the past 10 years, moderate droughts have been experienced, with the average annual rainfall ranging from 300 mm to 600 mm (Katambara and Ndiritu 2007). Between 2014 and 2016, the catchment area experienced a meteorological drought, which was characterized by reduced seasonal rainfall and high temperatures. It led to rivers drying up, leading to a lower groundwater table, deteriorated water quality, dry land and high animal mortalities (Rakgwale and Oguttu 2020). During this period in particular, the conflict between available water for e-flows and water for livelihoods and commercial agriculture and urban water supply became strongly evident.

Water resources in the Letaba River are under pressure as there is high demand with limited availability (Querner et al. 2016). Dams have been built and boreholes drilled to reconcile the demand and supply in the river system. There are three major dams in the river basin, each with a capacity exceeding 60 Mm^3/a, coupled with 3,000 boreholes (Katambara and Ndiritu 2007). The hydrogeological region is characterized by fractured aquifers with different water yields. The main aquifers are from highly permeable fractured rocks with limited storage capacity. The yield diminishes during the dry season if the volume of storage is limited or if there has not been enough recharge. Groundwater in the Letaba catchment has declined over the years, resulting in levels falling below the streambed level and leading to a declining base flow contribution to streamflow (Katambara and Ndiritu 2007). Thus, despite the high number of boreholes, there has been a constant increase in unfulfilled water demand. There has also been an escalation of social, economic and environmental activities in the river basin, including irrigation, mining, industries and recreation, in addition to the need to maintain a minimum flow for ecological concerns. Subsistence agriculture is extensive in the Letaba River Basin but with low input levels as the farmers here mostly rely on natural resources. Smallholder farm irrigation is practised mostly in the former homelands, which depend on rainfed production. These farms are characterized by a low level of production, mainly for subsistence, with only small surpluses marketed (Wichern 2013; Querner et al. 2016).

Irrigation is one of the main water uses in the Letaba River Basin, however, in respect of smallholder farms little is known about the quantity of irrigation water used (Wichern 2013), the extent of livelihood dependence on river flows, and how changes in flow rates might affect livelihoods.

Detailed information on the sustainability of the smallholder livelihoods dependent on river flows in the

Letaba is lacking. This research project was aimed at addressing this information gap by evaluating the effects of altered river flows on the livelihoods of vulnerable human communities in the Limpopo River Basin, specifically in the Great Letaba River. With a view to providing a context to the rest of the Limpopo Basin, we evaluated the socioecological consequences of the trade-offs between providing e-flows and supplying water for agriculture to maintain sustainable subsistence harvesting by vulnerable African communities in the Great Letaba region. The Great Letaba case study characterizes the relationship between sustainable e-flows in the river and the water requirements of sustainable agriculture, and evaluates the contribution of river flows to agriculture for livelihoods and the consequent risks to agriculture when river flows are available, reduced or absent. We took a probabilistic modeling approach to evaluate the potential risk of altered river flows to subsistence agriculture. This approach was used to generate conceptual impact pathways and quantitative models to forecast decision outcomes representing the potential risk of altered flows to subsistence agriculture (Whitney et al. 2018a). This step includes collaborative model development with small-scale farmers and stakeholders to assess farming futures given e-flow forecasts under different management options.

Aim of the Study

The study's main objectives involved the following actions:

i. Identify and characterize the local communities' use of the Great Letaba River's water flows for different livelihood activities, including small-scale agricultural processes (irrigated and dryland agriculture), fishing and livestock. This included consideration of groundwater for subsistence agriculture where it can reasonably be associated with river flows.

ii. Relate water availability and e-flows for ecosystem maintenance in the river to the seasonal requirements of small-scale agriculture and other livelihood activities.

iii. Determine opportunities and constraints faced by local women and men in developing sustainable agriculture and livelihoods in the area.

iv. Determine the small farmers' vision and priorities for successful and sustainable agriculture.

v. Develop a collaborative socioecological probabilistic model with local stakeholders to represent and evaluate the consequences of future water use and protection (including e-flow provision) in the Great Letaba River area.

vi. Determine the trade-offs between e-flows and water for sustainable agriculture in the Great Letaba River.

General Methodology

Description of the Study Area

The study area includes the Great Letaba River, upstream of South Africa's Kruger National Park (Figure 1). It lies in a summer-rainfall subtropical area with the rainy season commonly starting in October and lasting until March (Wichern 2013). Precipitation in the area is influenced by the regional catchment topography, resulting in less than 300 mm/a of rainfall in the lowlands and more than 1,200 mm/a along the escarpment in the upper catchment. Average potential reference evapotranspiration ranges from 1,100 mm/a to 1,300 mm/a. More than 85% of the rainfall occurs within the summer months (October-March). After a dry winter, rainfall increases rapidly only from November and December, before steadily rising during January and February and then rapidly declining from March onward (Schultz 1965). The peak of the rainy season coincides with the maximum frequency of occurrence in the annual cycle of tropical disturbances that control the summer rainfall season to a large degree (Tyson and Preston-Whyte 2000). Three major communities located in proximity to the Great Letaba River formed part of this study: Prieska, Mahale and Ga-Selwana as shown in Figure 1.

Data Collection

Methods to Identify and Characterize Livelihood and Small-scale Agricultural Activities

An initial social assessment of the study communities, livelihoods and small-scale agriculture was documented through a literature review and focus group discussions with community members. This provided a basic picture of the livelihood patterns practised by communities in the Great Letaba River region and an indication of their relationship with the river, their key priorities and activities. Outcomes from the study provided the context of the area which was used later for a detailed evaluation of the sustainability of agriculture in the catchment. The baseline survey was conducted through focus group discussions and interviews with small-scale farmers in the local communities. These group discussions and interviews identified ecosystem services available from the Great Letaba River including small-scale agriculture, general livelihoods and water-use demands through the years. During the interviews and discussions, a participatory mapping exercise was conducted in the three study communities (Prieska, Mahale and Ga-Selwana) to evaluate how each community's members use the river flow-related ecosystem services for local livelihoods. Landsat imagery of the area and a catchment map were used for the participants to draw on and show areas and points along the river that are important for ecosystem service provision. After the discussions and interviews, the researchers returned to each community to conduct a visioning exercise on the sustainability of the communities' livelihood activities and subsistence agriculture. The visioning process was important to understand the smallholder farmers' vision for their crops and how changes in the river's flows and stressors may affect the attainment of that vision and the SDGs relevant to them.

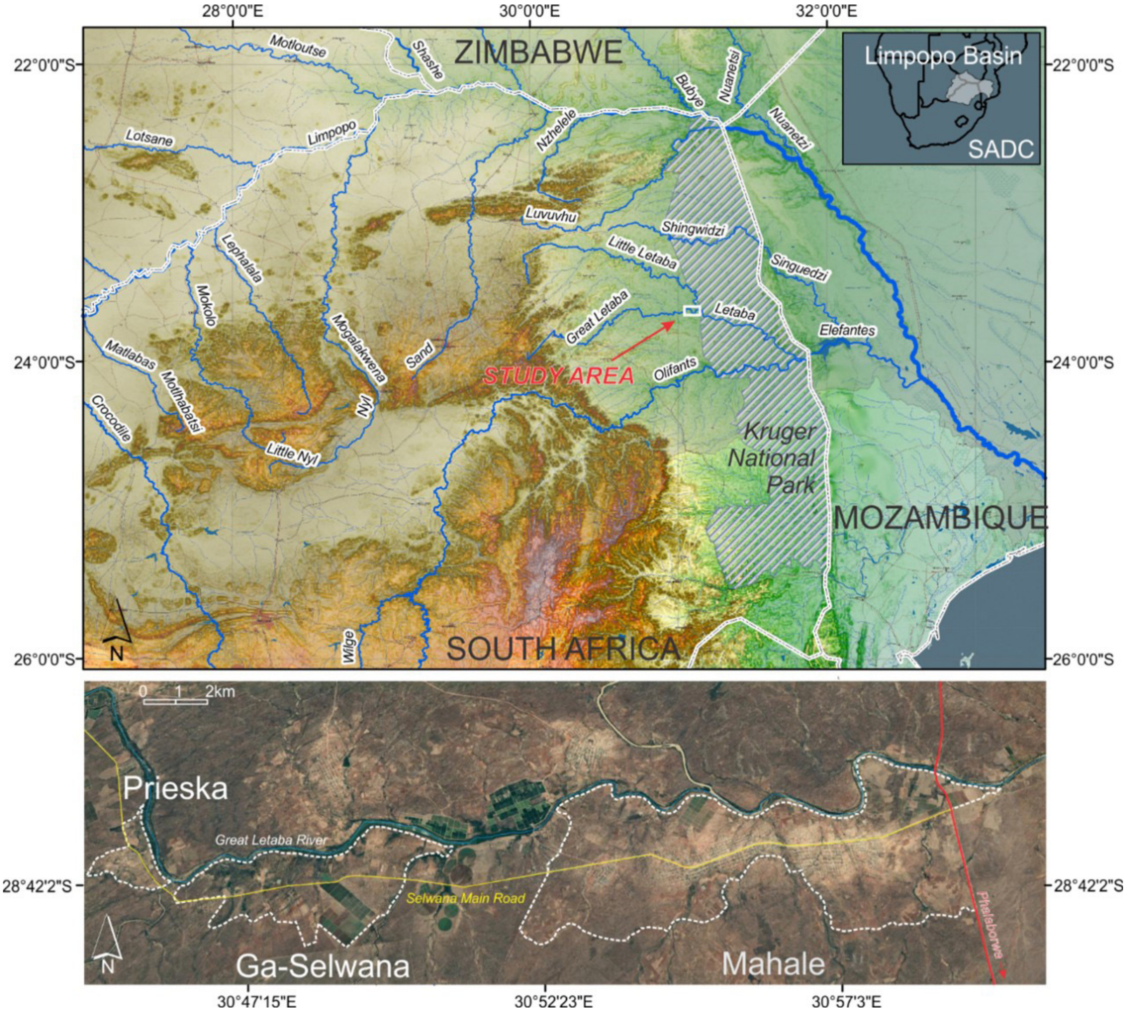

Figure 1. Map showing the location of the Great Letaba River study area including the study sites Prieska, Ga-Selwana and Mahale communities within the Limpopo Basin, southern Africa.

This research is embedded in the gender-aware approaches of the CGIAR Research Program on Aquatic Agricultural Systems (AAS) as explained by Estrada-Carmona et al. (2020) in a study in Zambia that adopted the use of these approaches. Gender-aware approaches are important since men and women hold different views and knowledge and use natural resources differently. In this research, sex-disaggregated data were collected across the study communities with the aim of understanding and comparing the extent of flow-related ecosystem services, challenges and opportunities between women and men.

Target Population and Sampling Techniques

Before any of the above-mentioned data collection activities were carried out, a 'familiarization' of the catchment area was undertaken. This exercise presented opportunities to engage with members of the catchment community, which comprised mainly small-scale farmers.

It was meant to get conversations started so that the researchers could get to know the potential participants and identify the target population. The target population of the study were mainly small-scale farmers from the local communities who are water users of the Great Letaba River. The selection of participants was guided by Etikan et al. (2016) who recommend purposive sampling in case studies to allow in-depth analysis of the phenomenon under study. Participants were recruited randomly at first; thereafter, additional participants were recruited through direct recommendations by other participants, in a method called snowball sampling. As per the criteria for selection, participants had to be small-scale farmers from the community who live in the Great Letaba River area and use the river waters. After the participants' consent was obtained, data collection was carried out during May and June 2021. The target participants were engaged at different times using different research methods as shown in Table 1.

Table 1. Description of the target population group, research and sampling methods.

Research methods	Target population	Sampling method
Focus group discussions and interviews	Small-scale farmers in three study sites in the Great Letaba River Basin	Purposive and snowball

The objective of the fieldwork was to determine subsistence use of river water and livelihoods related to flows in the Great Letaba River. This included groundwater use where it can be possibly associated with the flow of the river. This was determined through focus group discussions, interviews with community members and field visits over two months. The data collected were validated through field tracking (where the researcher is accompanied by a local key informant to identify the key features mentioned by the participants with the assistance of aerial photos). Field tracking validated the information provided by participants on ecosystem services and cultivated crops.

Data Interpretation and Analysis

Recordings of the group discussions and interviews were transcribed from the local language Xitsonga into English. The transcripts and notes made by the researchers were subjected to rigorous content analysis to elicit information on how the river is used for livelihoods, especially small-scale subsistence agriculture. The content analysis helped in identifying themes for further discussion. Qualitative information gleaned from the transcripts on use of the river for agriculture and the farmers' vision on sustainability was analyzed with the web-based application Voyant Tools which detects frequently used words, related descriptors and associated link patterns in a transcript (Welsh 2014). Voyant clears any biases the researcher may have had when identifying the common themes.

Procedure to Link Small-scale Sustainable Agriculture to E-Flows

A key aspect that facilitated the linking of e-flows and sustainable agriculture was the development of a conceptual model as shown later in the section *Modeling the Contribution of E-Flows to Sustainable Agriculture, Food Security and Livelihoods*. Focusing on the Letaba River as a test case, participatory, holistic modeling techniques were used to conceptualize the contribution of e-flows to subsistence agriculture, food security and livelihoods, and to generate conceptual impact pathways and quantitative models to forecast decision outcomes (Do et al. 2020; Lanzanova et al. 2019; Whitney et al. 2018a, 2018b). This included collaborative model development (Whitney et al. 2018a) to assess farming futures given e-flow forecasts under different management scenarios.

In South Africa, the e-flows constituting the ecological reserve requirements for the Letaba River have been established through the application of the Resource Directed Measures procedure (DWAF 2006), as required by the NWA (NWA 1998). The Department of Water and Sanitation (DWS) selected a range of sites to represent the ecosystem variability of the river basin and determined the reserve or e-flow requirements for these sites (DWS 2017a). The Great Letaba River was included in our study as there is a DWS site called Letaba Ranch (GLET-B81J-LRANC) downstream of our study area but upstream of the boundary of the Kruger National Park. We used the outcomes of the DWS e-flow assessment to represent the e-flows for the Great Letaba River considered in this study. No additional hydrological modeling to determine e-flows was undertaken for this study. The e-flow data and information used in this paper, therefore, is mainly based on results from a hydrological study (DWS 2017a) carried out as part of a Limpopo monograph study (LIMCOM 2013) as well as data from a Limpopo reconciliation study (DWS 2017b). These latter two studies undertook detailed assembly and processing of hydrometeorological data, historical water-use collation, and long-term natural and present-day streamflow time series for the period 1920-2010 through calibration of the WRSM2000 model at different river gauging weirs in the Limpopo Basin.

Model Building Process

The model building process involved the co-development of a conceptual impact pathway describing the important interactions between the decision intervention options and the expected outcomes. In this step, we worked with experts to elicit all the important interactions and factors that influence the relationship between e-flows and sustainable agriculture. This conceptual model was then translated into a mathematical model that describes the current state of knowledge (see Annex 1 for the model scripts). An input table to store the estimate values (Annex 2) that feed into this mathematical model was designed. Literature and all other sources of data including the experts' own knowledge were consulted to define the confidence intervals related to important values in the model. The conceptual model used the evidence gathered in the field surveys to develop a hypothesis on the relationships between the multiple sources that impact subsistence agricultural water use, e-flows and livelihoods. A set of decision analysis methods was applied to make use of existing knowledge to describe the complex relationship between e-flows and agricultural livelihoods and to support decision-making. Models were generated based on the current state of knowledge, and using these data to make forecasts of decision outcomes. In cases where hard data was missing or unattainable for important variables, following the principles of decision analysis, forecasts of decision outcomes without precise numbers were made as long as probability distributions describing the possible values for all variables could be estimated.

Our study used participatory methods, following Whitney et al. (2018a, 2018b), to develop the conceptual model of the e-flows decision context. These procedures were formulated in such a way as to help stakeholders and decision-makers work together to generate an impact pathway that expresses the logical connections between the intervention (in this case the e-flows options) and the outcomes (effects on smallholder farmers' cropping systems). This required several rounds of discussion and feedback in the larger plenary and in smaller groups. The workshop took place with seven experts, two of whom had recently completed scoping fieldwork in the region. However, due to the Covid-19 pandemic, we were unable to conduct this workshop in person. Instead, we held an online workshop with a small group of project partners. We gathered ideas and used break-out rooms and plenary sessions to draw the impact pathways together using simple collaborative online drawing tools. While this mode of operation proved adequate for generating the model presented here, a more intensive in-person exercise may have generated richer results, e.g., on potential implications for upstream water users. The developed conceptual model was used to generate an R function that takes in the variables provided in the input table and produces a model output. To build these simulations, we used functions from the decisionSupport (Luedeling et al. 2021), dplyr (Wickham et al. 2022), nasapower (Sparks 2018), patchwork (Pedersen 2020), tidyverse (Wickham 2022) and evapotranspiration (Guo et al. 2022) libraries in the R programming language (R Core Team 2021).

Scenarios

To explore the impact of alternative e-flow implementations, we compared outcomes in three scenarios:

a) **UNRES** – *baseline, unrestricted water use*

This scenario is based on the observed river flow, without considering any e-flow requirements. Smallholder farmers can extract water needed for irrigation until the river flow falls below the minimum level needed to operate the pumps.

b) **EFLOW** – *E-flow through abstraction control (without using dam releases)*

This scenario simulates an e-flow policy that provides e-flows by limiting the withdrawal of water to quantities that are available above the e-flow volumes and does not supplement with dam discharges during times of shortfall.

c) **SUPPL** – *E-flows achieved through abstraction control and dam releases*

In this scenario, e-flow volumes and the requirements of smallholder farmers are ensured in times of shortfall through supplementation from existing upstream dams (reservoirs) in the basin. Here, e-flows and subsistence agricultural needs can always be assured through dam releases.

Model Assumptions

Agricultural realities are complex, and models cannot fully capture all nuances of agricultural systems, especially where time and budget for model development are limited. Through our decision modeling approach, we compensated for this deficiency by explicitly considering uncertainties in our simulations. Nevertheless, a few assumptions were made in developing the model, as follows:

a) All farmers fully comply with e-flow policies.

b) River flow and e-flows are considered at monthly intervals, even though both fluctuate over shorter durations.

c) Farmers cultivate crops with water requirements that correspond roughly to the potential evapotranspiration as computed by the Hargreaves-Samani equation, with a small error margin indicated by crop coefficients varying between 0.9 and 1.1 (90%

confidence interval). We assumed that this represents the average water need across all irrigated farmland in the community.

d) River flow measured by gauge at the site GLET-B81J-LRANC represents the river flow at our target communities.

e) Previously gazetted e-flows have not had a major influence on flows. Applicable e-flows include gazetted flows as per DWS (2017a).

f) Agricultural outcomes related to e-flows can be expressed by the crop water gap, i.e., the relative shortfall of available water compared to the overall water demand for agricultural crops.

g) It was assumed that upstream dams would be able to provide supplementation of flows if required. This assurance is not studied in this project.

Simulations

To simulate agricultural outcomes for the three e-flow scenarios, functions of the decisionSupport package for the programming language R (Luedeling et al. 2021) were used. This package provides a function to compute plausible distributions of model outcomes through a Monte Carlo simulation. In a Monte Carlo simulation, a large number of random values are drawn for each input variable according to user-defined probability distributions. The model is then run for each combination of values, with the resulting population of model results assumed to represent the plausible distribution of outcomes. In contrast to the precise values produced by fully deterministic calculations (which do not consider uncertainties), these distributions reflect the limited predictability of the real world and the limitations imposed on the modeling process by the imperfections of our knowledge about all model input parameters.

The outputs of a Monte Carlo simulation are useful for bracketing the plausible range of system outcomes. They also offer an opportunity for further explorations, especially when the simulation is run with uncertainty estimates that approximate the current state of knowledge. In such cases, the outcome distribution can be related to variation in all input parameters to identify important uncertainties, which determine the magnitude of expected outcomes. Additional precision on system outcomes may then be gained by measurements of highly influential variables. The decisionSupport package implements such analysis in the form of Partial Least Squares (PLS) regression, whose 'Variable Importance in Projection' (VIP) scores identify important variables.

Wherever a model simulates a decision between alternative options, e.g., whether or not to implement an e-flow policy, further opportunities for decision support arise in cases where no clearly preferable option is indicated by the Monte Carlo results. This is the case whenever model outputs are split between runs indicating different options as preferable. Such a scenario lends itself to an evaluation of the 'Value of Information' (VoI). The VoI is a metric that describes the value of additional knowledge on a particular variable to a decision-maker faced with a choice between alternative options. It is based on a quantification of the damage incurred by choosing the option that ultimately ends up generating inferior results. The chance of making a poor choice (in hindsight) can often be reduced by additional information, and the VoI represents an attempt to quantify the value of this information gain. In decisionSupport, this calculation is implemented through the 'Expected Value of Perfect Information' (EVPI), which is based on the (usually unattainable) state of perfect information on a particular variable. The EVPI can be understood as the maximum amount a rational decision-maker should be prepared to pay to completely eliminate uncertainty on an uncertain variable. In most decision simulations, few variables, if any, are so influential that additional information on them can change the decision recommendation that results from the simulation. Where such high-value variables are identified, the respective uncertainties emerge as promising entry points for decision-supporting research.

All major elements of decision analysis are provided in the decisionSupport package (Luedeling et al. 2021), which we used to conduct simulations, identify important variables for the simulated outcomes and search for high-value variables in a decision-making context.

Community Situation Analysis

Upon completion of the field survey in the study area to identify and characterize the livelihoods and use of the Great Letaba River, the following results were obtained.

Participants' Demographics

The study interviewed 72 participants who were directly benefiting from the river flow. Their demographics are shown in Table 2. The main consideration in these interviews and group discussions was how water from the Great Letaba River was being used and how changes in the river flow over the years had impacted the respondents' farming and other livelihoods. We also identified and discussed the crop types, amount of water used, and the water-saving and sustainable-farming techniques and practices employed by the participants. The results from these interviews and group discussions showed that the communities used the Great Letaba River for subsistence activities such as crop irrigation, livestock farming, sand mining and fishing in addition to cultural and spiritual rituals.

Table 2. Participants' demographics.

Gender	Age range	Years of residence in the area	How people use the river
31 male; 41 female	23-65	3-65	56 crop irrigation 10 livestock production 5 fishing 2 sand mining 20 cultural and spiritual rituals

Many of the respondents have been living and farming in this area for 3-65 years; they know much about water use and agricultural production in the local community. About 57% of the 72 participants we interviewed were women and 43% male. Most of the women worked in groups (8 farming cooperatives), tending to 0.5-10 ha of land. Only one farming association had males. Most of the men farmed individually with their land size ranging from 2 ha to 18 ha. Agriculture along the Great Letaba River is a mostly low-input activity that utilizes mainly natural resources. More than 70% of the farmers interviewed were older than 35 years with less than 5% having tertiary qualifications. Most of the participants used water for crop irrigation (over 70%) with less than 15% using it for livestock production followed by about 3% for fishing. Other uses included cultural and spiritual rituals and drinking.

Subsistence Water Use for Agriculture

Agriculture provides the base of the economy in this region. The Great Letaba River sub-basin is a highly productive agricultural area with mixed farming including livestock, irrigated cropping and fishing. The most grown crops are okra, tomato, green pepper, cabbage, beetroot, eggplant, butternut, baby marrow, chili, onion and watermelon, all of which use irrigation water from the river or from groundwater. Due to high demand and limited availability, water resources in the Letaba catchment are under pressure. With increasing incidence of drought, flows have been decreasing (Kanjere et al. 2014; Sinha and Kumar 2015), affecting agriculture significantly.

Most of the crops are grown with supplementary irrigation. Through the dry season and to supplement shortages during the rainy season, water is pumped daily from different points of the river. Farmers mostly use surface water if their farm is situated close to the river. Three farmers said they rely on groundwater from boreholes 50-100 m deep that yield 0.5-5 l/s (Querner et al. 2016). Okra, a popular vegetable which originated in the hot climate of Africa (DAFF 2012), is the most preferred crop as it is profitable, drought-tolerant, water-efficient and requires low farming inputs. It is usually planted between February and May with regular irrigation in the first two weeks after planting. It is harvested two or three times a week as regular picking increases yield.

Estimated Agricultural Crop Water Use and Planting Times

We estimated subsistence water demand and use for crops on the basis of the farmers' water use per day. Irrigated agriculture accounts for a major part of water use in these communities. Our analysis showed that irrigated subsistence agriculture used an average of 280 m^3 of water per day for an estimated total of 185 ha under subsistence crop agriculture, with farm sizes ranging from 0.5 ha to 18 ha. Okra was the most preferred crop grown in these farms, irrigated with an average of about 1,000 liters of water per ha per day. Water was lifted using motorized pumps from the nearest point along the river. Drip irrigation was used in 90% of the farms, making it the most common irrigation type in the area. Sixty percent of crop farmers practised supplementary irrigation. Crops are sown at the start of the rainy season from November to January. Crop water use from the Great Letaba River is highest in the summer rainfall months from November to April during critical stages for the crops (Table 3). In a good year with adequate rains, the river flow is sufficient to meet irrigation demand. However, river flows fluctuate, and irrigation water shortages occur when the flow goes low during the dry months of the year and during drought seasons. The lowest river discharge occurs from June to December. Farmers leave part of their land fallow between July and September because of insufficient water flow in the river, and their crops fully rely on irrigation during this time. The insufficient availability of water during this period is substantiated by the river's hydrograph in Figure 2.

The graph in Figure 2 shows how flows in the Great Letaba are distributed over the months of the year. High flows occur between March and July and low flows between August and January. As a result of the varying volume, timing, duration and frequency of seasonal flows, it has become essential for local communities to plan their livelihoods based on flow patterns. The graph shows how farmers time their planting to correspond with the flow patterns. They plant most of their crops, as shown in Table 3, early in the high flow season and target the crop's critical periods (e.g., when crop water requirement is high) to coincide with the peak flow period (January-March).

According to participants in our study, the Great Letaba River's flow regime has changed over time: reduced flows are now experienced in December during the planting season for most crops. Late rains have been experienced as well as flash floods. Water shortages and very low flows are most common between June and December. Sedimentation in the river has increased due to increased sand mining, and this has a major influence on abstraction of water as depth is reduced. The most severe water flow reductions in the river have been observed between June and November. According to the participants, disconnectivity of the river water was observed during the low-flow season in the dry years between 2016 and 2018. Parts of the river went dry and water abstraction was not possible at some points as flow velocity and depth decreased. According to the participants, the river's

Table 3. Planting times of major crops for subsistence farming along the Great Letaba River.

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Okra		🟧	🟧	🟧	🟧	🟧						
Tomato	🟧	🟧									🟧	🟧
Cabbage	🟧	🟧							🟧	🟧	🟧	🟧
Eggplant	🟧	🟧	🟧	🟧								🟧
Chili/peri-peri	🟧	🟧	🟧	🟧	🟧	🟧						
Dry bean	🟧	🟧	🟧	🟧	🟧							
Onion	🟧	🟧	🟧									
Beetroot	🟧	🟧	🟧	🟧							🟧	🟧
Butternut	🟧	🟧	🟧	🟧							🟧	🟧

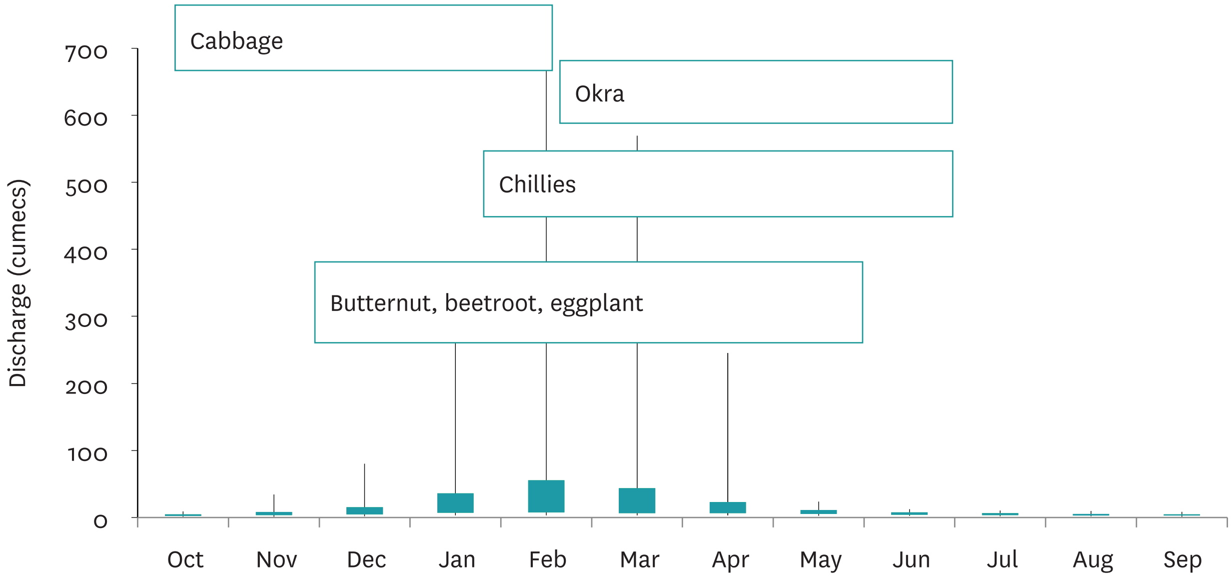

Figure 2. Box and whisker plots showing the total flow variability throughout the year and the planting times of selected crops in the Great Letaba River catchment.

Note: The boxes represent the 15–85 percentiles and the whiskers represent the range from 0.01 to 99.9 percentiles.

inherent water connectivity was reduced by heaps of sand which disrupted flows from upstream to downstream. Disconnectivity was also experienced laterally. Due to drought conditions in 2016 and 2018, farmers' boreholes ran dry, increasing their pumping depth and time, which led to higher operational costs.

Estimated Crop Yield

In the best season, the farmers produce an average of about 400-800 kg/ha of okra and 1,000-5,000 kg/ha of tomatoes (Table 4). However, yields went down to 300 kg/ha during 2016-2018 because of high temperature and drought.

Of the 72 crop farmers, 62.3% said 1999/2000 was the best agricultural season they have had in recent years as yields and prices were both high that year. On the other hand, 30% of the farmers described 2000 as their worst year because floods early in the cropping season had destroyed their crop. However, 65% of the farmers said they had their worst seasons during 2016-2018 as there was drought throughout that period. Figure 3 compares the expected yield of crops and the farmers' best yields, as seen in 1999/2000. About 55% of the farmers experienced yields deficient by more than 70% even in their 'best season'. The lower-than-expected yields were attributed to water shortages.

Figure 3 shows that green beans had the highest yield gap of 66%, eggplant 56%, cabbage 50% and okra 33%. Low yield gaps of 10% were experienced with beetroot and butternut, with dry beans doing well with no yield gap. According to the farmers, green beans did not do well because of a fungal infection, which rendered most of the produce unacceptable in the market. High rainfall

Table 4. Subsistence farmers' average yield and selling price of crops grown along the Great Letaba River.

Crop	Yield (kg/ha)	Average price (ZAR/kg)
Tomato	1,000-5,000	7.5
Okra	400-800	12.5
Cabbage	4,000-6,000	10
Chilis	1,500-2,500	20
Dry beans	1,500-2,000	20
Green beans	400-1,000	17.5
Eggplant	2,500-3,500	4.8
Beetroot	5,000-8,000	7.5
Onion	8,000-9,000	6.5
Butternut	6,000-8,500	8

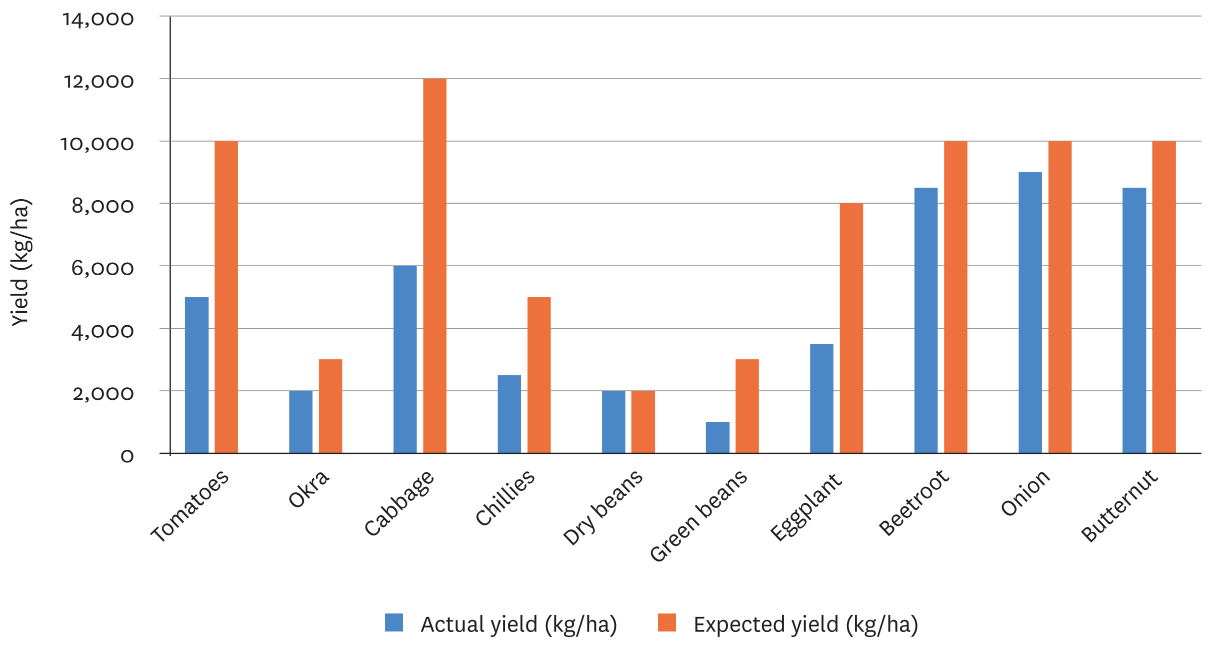

Figure 3. A comparison of the actual yield and expected yield of different crops in the farmers' best season (1999-2000).

accompanied by floods were experienced in the year 2000, as Reason and Keibel (2004) reported, with South Africa receiving 400–550 mm of rainfall, about three times the February mean, which damaged agricultural land. The floods of 2000 also had significant impacts within the Limpopo River with flows rising to the highest levels in over 15 years (Dartmouth Flood Observatory 2000). According to participants in our study, the floods that year washed away their crops, most of which they had planted in February.

Major crop yield decreases were experienced during the 2016 and 2018 seasons too, according to the study participants. There was an early cessation of rains and poor rainfall distribution between January and the end of the planting season. The years 2016-2018, described by 65% of the farmers as their worst seasons, witnessed drought incidence throughout that period, which coincided with the critical reproductive and flowering stages of most crops. Maize and okra crops dried up prematurely during this period. According to Rakgwale and Oguttu (2020), extreme dry conditions had culminated in a meteorological drought in different parts of the Limpopo region between 2014 and 2016. During the 2016-2018 drought, depth and flows of river waters were both low with flows ceasing totally in some parts of the river. Farmers recalled that they had to dig wells instream to allow pumping, which increased their pumping time and operational costs. Some of their groundwater sources too ran dry.

About 65% of the farmers noted that the 2016-2017 cropping season was their worst as they got the lowest yields than expected with a yield gap of 50-87% for different crops (Figure 4). Eggplant performed the worst with a yield gap of 87%, followed by cabbage (83%) and tomatoes (85%). Green beans, beetroot and butternut had yield gaps of 76%, 70% and 75%, respectively. Dry beans had the lowest yield gap of 50%.

According to the participants, the river's flow regime has changed over time. Reduced flows are now experienced in December, compared to the situation in the 1930s when they used to receive high rains coupled with increased flows (Figure 5) during that month, which was the planting season for most crops. Later rains have been experienced since the 1990s, frequently accompanied by flash floods. Figure 5 shows that although in the years 1987 and 1938 the rainy season started in December, the flow was higher in 1938 compared to 1987.

Sustainable Water-use Practices in Subsistence Agriculture

According to Evans and Sadler (2008), irrigation (usually formal, commercial irrigation) accounts for a major share of the consumption of freshwater in most rural communities. But it is necessary for increased income and for economic advancement. There is competition for freshwater, which makes it imperative to maximize productivity per unit of water consumed. Thus, it is important to identify measures that agricultural users can adopt to maximize water productivity in sustainable agriculture while remaining sensitive to societal needs. The main aim of this research was to determine the sustainability of smallholder farmers' practices. Given increasing demand and limited water resources, there is a need to maximize the use of available water, which, however, can conflict with sustainable management

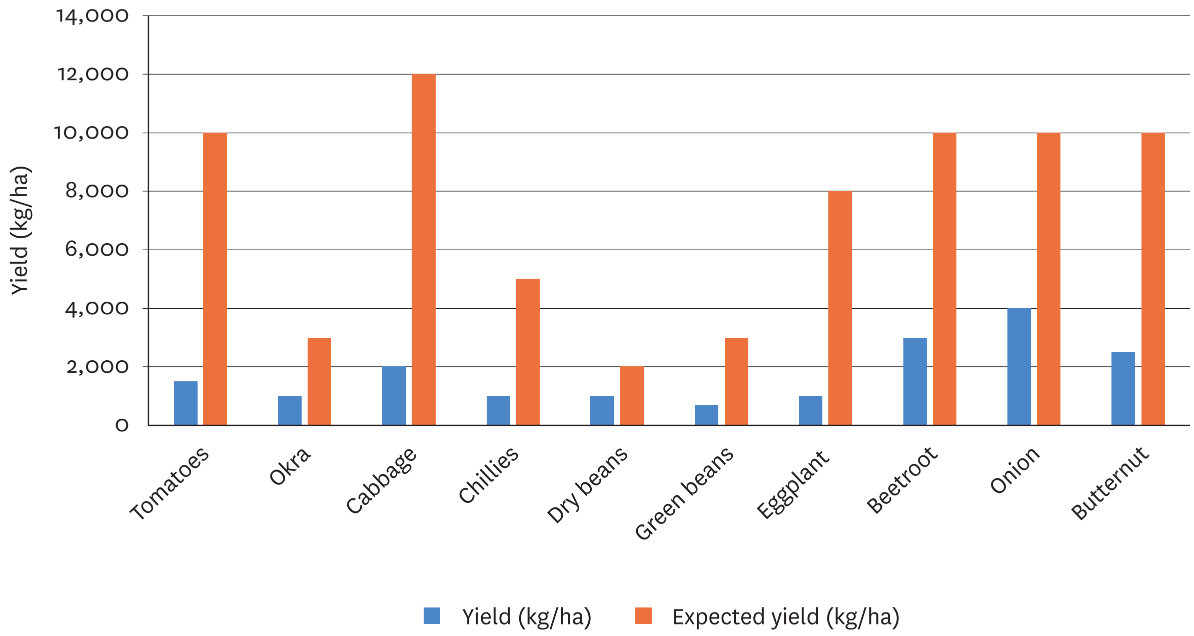

Figure 4. A comparison of actual and expected crop yields in the farmers' worst season (2016-2017).

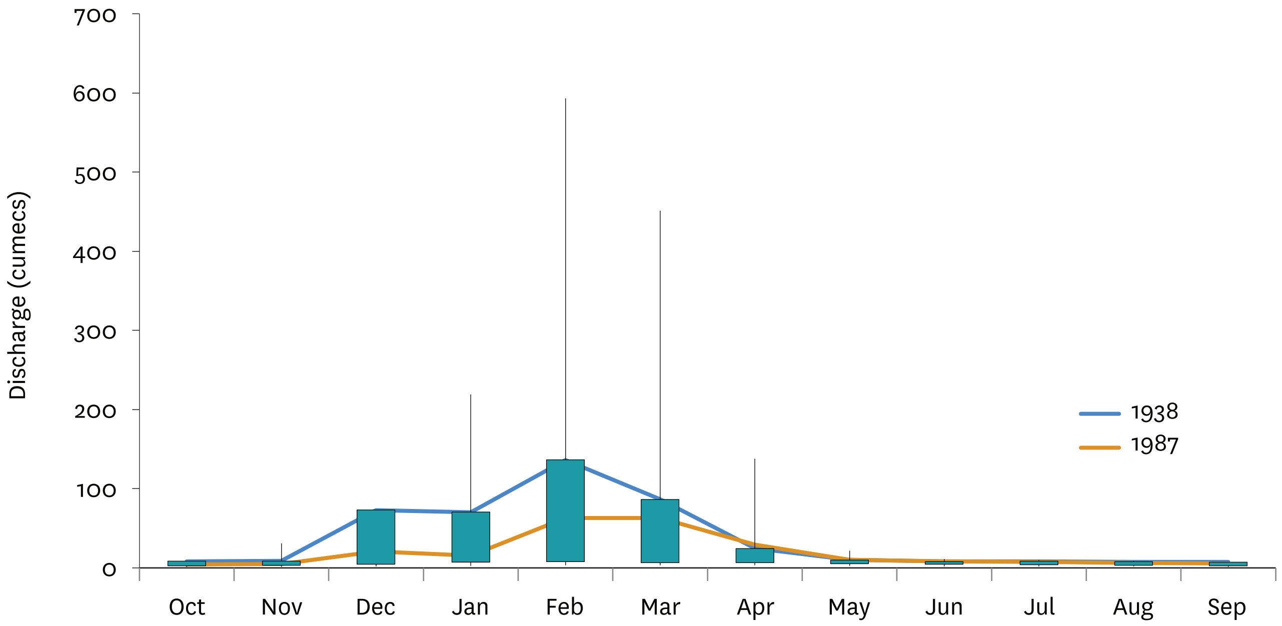

Figure 5. Box and whisker plots of the total flow variability throughout the year with average months compared with past river flows (1987 and 1938) in the Great Letaba River catchment.
Note: The boxes represent the 15–85th percentile and the whiskers represent a range from the 0.01 to 99.9th percentile.

of water resources. According to Azman et al. (2012), sustainability of agricultural activities is intended to achieve economic efficiency, environmental quality and social responsibility. Musvoto et al. (2015) reported that although smallholder farming may use low technology and inputs, and may have negative sustainability impacts, several approaches have been advanced to improve the crop yield per unit of water consumed. In this study, participants were asked about the sustainable farming techniques they practised to maximize water-use efficiency. The most-used practices were dig-up pits to determine irrigation time, planting pits to maximize water use and ridged furrows. Shade nets were only used by five farmers. These are practices aimed at reducing non-beneficial water consumption and soil evaporation, especially during periods of low river flows.

Dig-up Pits to Determine Irrigation Time

Some farmers said they use dig-up pits on their farms to assess the available soil moisture before irrigation. If the soil looks dry at more than 5 cm, it means it is time for irrigation. This is a most common practice employed during the mid-early growth stage of the crop (tubing or flowering) when crop water demand is high. It is done to cut pumping costs: farmers try to use less than 10 liters of petrol per day to pump. Farmers also tend to decrease irrigation time when the crop or vegetables have matured. The participant farmers said they introduced dig-up pits on the advice of extension officers after experiencing reduced crop yields and deterioration of yield quality on most farms. However, not much attention is given to irrigation scheduling parameters like crop growth stage and sensitivity to water stress, climatic conditions and water availability in the soil while deciding when to irrigate, how much water to use or the appropriate irrigation frequency. Generally, irrigation is scheduled early in the morning or late in the afternoon to minimize evaporation loss. On average, about 1,000 liters of water is used to irrigate one hectare in a day, without taking into consideration variables relating to crop water need such as crop type and crop stage.

According to Evans and Sadler (2008), reduction of water loss in agriculture requires irrigation application by precision-propelled irrigation systems. Of the farms we visited for this study, 95% were under drip irrigation, which is preferred for its high water-use efficiency in terms of reducing soil evaporation and maximizing crop water productivity. This irrigation system offers high levels of water savings because of its high precision (Evans and Sadler 2008).

Soil Hilling

Soil hilling (Figure 6) is practised by farmers in the Great Letaba River communities to channel soil surface water flow. Farmers manually excavate the soil to form a hill with a pit on top. The planting pits harvest precipitation and minimize water runoff, thereby increasing infiltration. The holes are dug 30-100 cm apart with a depth of 5-15 cm to prevent runoff. This practice is used for annual and perennial crops, e.g., maize, sweet potato and bananas. In the case of Figure 6, the pits were prepared for sweet potato planting. Manure and/or fertilizer are added to each pit if available. Planting in pits and soil hilling has been promoted to improve the water holding capacity of soil and increase crop yields, a view shared by most farmers. However, making the soil hills and pits is labor-intensive; in the Great Letaba communities, it is practised on less than 1 ha.

Tied Ridges and Furrow Blocking

Tied ridges increase soil water retention and make water available to plants by collecting water in the furrows. Planting takes place on either side of the furrows, where the water infiltrates. The furrows are dug at shallow depth along the contour line of the slope and making ridges on the lower side of the furrows. Water is trapped in a furrow for plant watering (Figure 7). Only 5% of the crop farmers use furrow irrigation, and in particular ridged furrows.

Shade Netting

Some farmers use systems like shade netting to reduce evapotranspiration by protecting plants from harmful sun rays and minimizing soil moisture loss. Shade netting comes in different densities and colors.

Figure 6. Soil hilling and preparation of planting pits (a water-saving technique) (*photo:* Authors' photo taken during fieldwork).

Figure 7. Furrows and the watering process (*photo:* Authors' photo taken during fieldwork).

Intercropping

Local on-farm water-saving and sustainable-agriculture techniques also included intercropping of legumes and vegetables to save on water, especially on farms practising furrow irrigation. These strategies incorporate alternative cropping systems including winter crops and deep-rooted cultivars that maximize the use of stored soil water and some nutrients.

The Letaba River area experiences hot summers, with frequent moderate droughts experienced over the years (Katambara and Ndiritu 2007). However, there are minimal crop and water-saving techniques practised in the area. There is not much optimization of water use to minimize evapotranspiration and seepage losses. The decision support processes for water use do not consider crop water use and application efficiencies to minimize water use in these farms. Implementation of water-saving practices and technologies is limited to a few farmers. This suggests that available water is not maximized for productive irrigated agriculture. Improving irrigation efficiencies and sustainable water use in this area requires substantial investments by farmers in labor and infrastructure. These requirements are a major constraint to enhancing productivity and optimizing water use. The limited water-saving techniques have the potential to threaten e-flows as the demand for water is likely to increase with expanding agriculture. According to Salman et al. (2020), increasing productivity per unit of water used is an appropriate strategy to protect water resources. Water-saving techniques increase the productivity of agricultural water use in a sustainable manner as water resources use is minimized. This is mostly because, according to Brauman et al. (2013), crop irrigation consumes more water than any other human activity. Thus, to manage water resources, water sustainability in agriculture is important.

Livestock Farming Water Use

Some members of these communities (10) are engaged in livestock farming (beef production and goats). On an average, a cow weighing 400-500 kg retails for ZAR 10,000-15,000. Goats weigh 40-100 kg and retail for ZAR 800-1,000. Farmers in our study communities owned 10-40 heads of cattle and 5-30 goats. The water needs of livestock varied per season, size and feed. According to the participants, water demand increases during the summer season or when there are drought conditions. The average water requirement per day was estimated at 45 l/day per bull and 5 l/day per goat, as recommended by the Department of Agriculture. The livestock farmers explained that as the area has limited grazing land and fodder is expensive, their livestock sometimes graze along the riparian zone. So, high rainfall and floods at varying intervals are important to replenish the riparian grassland. The year 2000 was recalled by livestock farmers as a good year as they received very high rainfall in 1999 and early that year, which improved the veld condition. They did not have to buy fodder that year.

Fishing

Subsistence fishing is an important ecosystem service that contributes to the well-being of communities in the Great Letaba River region. In this part of the catchment, community members travel 3-6 km to different parts of the river for fishing. The most preferred fish are large, sharptooth catfish (*Clarias gariepinus*), cyprinids (*Labeobarbus spp. and Labeo spp.*) and tilapia (*Oreochromis mossambicus and Coptodon rendalli*). Many alien species including common carp (*Cyprinus carpio*), tilapia (*Oreochromis niloticus*) and bass (*Micropterus spp.*) are also targeted. According to the fishers, subsistence fishing is seasonal and coincides with the summer movement of fish. They target large specimens (>200 mm in length) that are available in summer compared to the small fish available in winter when the river flows are low. Fishing in winter or in the dry seasons is not preferred as the flows are low and the fishermen have to spend relatively more time (up to 4 times) for the catch compared to summer. In summer when the flow improves, fishermen can catch a 25-liter bucket full of fish within 2 hours while in winter, they may have to spend the whole day for the same catch. So, in winter, most of the male fishers pay more attention to their crops or find temporary jobs in the area, as fishing is not viable. During our survey, two female fishers were interviewed while fishing and all male fishers were in their fields. Female fishers mostly fish for household consumption and prefer shallow water due to safety concerns compared to males who mostly fish for income and prefer deep water to catch bigger fish. The risk of crocodile attacks is a real and present danger. Some attacks resulting in injury and death have been reported from the area.

Spiritual and Cultural Water Use

There are several sacred sites along the Great Letaba River where the local communities gather to perform rituals relating to ancestor worship and spiritual cleansing. The river's free-flowing waters are believed to have a spiritual power that is cleansing and wards off evil spirits. For example, rituals are conducted at some of these points to heal women who have lost their husbands or have had miscarriages. Participants in our study argued the importance of river flows for the cultural values held by their community. The cultural significance of the river to these communities is supported by Oestigaard (2009) and Rinne (2001) who report that flowing water is believed to be alive and life-giving because of its movement. Euzen and Morehouse (2011) describe river water as emerging from the depths of the earth, symbolizing virginity, purity and freshness. River flows connect with and sustain the cultural and spiritual beliefs and values of these communities. In our interviews with community members, participants said baptisms are carried out during the Easter holidays (March-April) targeting the high flows (Figure 8). The June-September period is reserved for traditional healers' rituals which are conducted during the low flow season. Children's baptisms take place in December when the high flow season is just starting.

Other than using the river for spiritual rituals, community members also harvest plants which include *Mimusops zeyheri* (called *nhlantswa* in Xitsonga and *mmupudu* in Northern Sotho) to treat gastritis diseases. According to participants, the *M. zeyheri* plant used to be found around the Great Letaba riparian area but disappeared during the 2016-2018 drought period. *M. zeyheri* is mostly found in Limpopo province and other areas to the north of South Africa on rocky hillsides, near riverine boundaries and in dry open woodland and bushveld (van Staden and Bredenkamp 2006; Rampedi and Olivier 2013). According to van Staden and Bredenkamp (2006) and Mphephu (2017), the roots of *M. zeyheri* have ethnomedicinal use in treating ulcers and wounds.

Gendered Perspective

Traditional agriculture in Africa is strongly gender disaggregated. We found that women participants in the Great Letaba River area tended to complement tractor weeding with manual weeding. We also found that soil and water conservation techniques were practised only by women, e.g., ridged fields and planting pits. Shaded nets on the other hand were only used on male-owned farms. Women and men had access to similar ecosystem services (fishing, irrigation water, cultural use, livestock grazing), but women's priority was to meet household food security needs rather than income. Although the participants in our study had been cultivating the same crops for the past five years, cultivation of maize (the staple food of the community) was discontinued on all male-owned farms due to low productivity. It was currently grown on five women-owned farms but only for household consumption. These contrasts show that fields cultivated by women tended to complement household diets, which is important for household food security. Similar contrasts were observed in the case of fishers. Of the five fishers we interviewed, two were women and three males. The women preferred to fish for the household diet and used the shallower areas while the men preferred deeper pools to fish for large species, which they hoped to sell. This indicates that women were more concerned about food security.

Land Restitution and Water Rights Politics

The subsistence farmers who were part of the study did not have water-use licenses since their volumes of water use were within the general authorization level. According to DWS (2016), general authorization allows use of water without a water-use license provided it is within the limits and conditions set out in the government Gazette Notice 40242 of 2016. According to these gazetted general authorization limits, a water user in the Limpopo Basin is allowed a maximum abstraction of 2,000 m^3 per year and up to a rate of 1 l/s at any time during the year. Also, not more than 50 m^3 per day of water can be abstracted from a surface water resource over a year if there is no license. If a water user's requirement is above the general authorization limit, and there is a high risk of impact

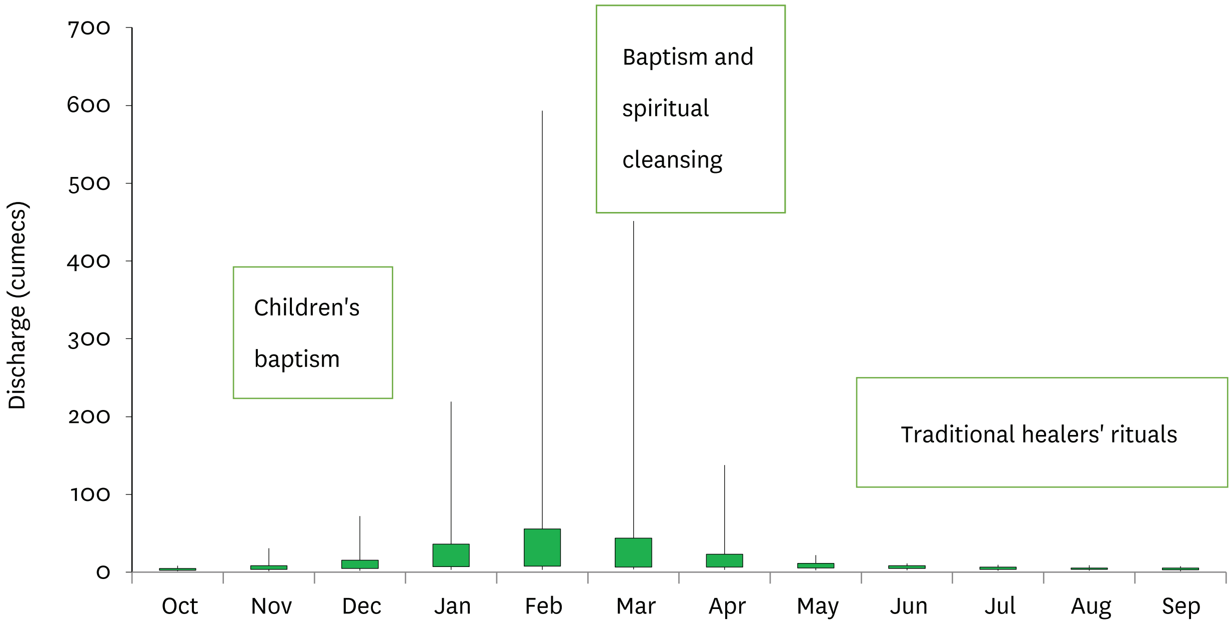

Figure 8. Box and whisker plots of the average monthly total flow variability and the timing of spiritual and cultural activities in the Great Letaba River catchment.

Note: The boxes represent the 15–85th percentile and the whiskers represent the range from the 0.01 to 99.9 percentile.

on water resources, a license is required, as defined in Section 21 of the NWA. According to the water-use license application procedure, water and land rights are tied together. Water-use licenses are issued to property owners (DWAF 2007); thus, only a property owner can apply for one, or the application must be accompanied by a 'permission to occupy' (PTO) letter. In cases where land ownership has changed, water rights can be transferred without a need to apply for a new license, if the water use is similar as used previously.

In the Letaba River area, most small-scale water users are not eligible for water-use licenses. According to these farmers, they often fail to obtain PTO documents that would allow them to apply for new licenses or gain transfer of water rights from previous landowners due to shortcomings in South Africa's land restitution program under which some of the farms in these communities were reclaimed post-1994. Land restitution has been one of the key issues in South Africa since the country achieved democracy in 1994. The main aim of the program was to redress the problem of racially motivated land dispossession which took place during the apartheid era (pre-1994). Mandated by the Restitution of Land Rights Act, the main objective of the program is to make a provision for the restitution of land rights to people who were dispossessed. One main challenge faced by the program, however, has been that the water rights attached to a piece of land are not registered as part of the land entitlement. Thus, some small-scale farmers in these communities have the land but cannot access water as the water rights remain with the previous owners.

There have been some controversies between the traditional authorities and former farm owners as there is now a perception that the land is under lease with the former landowners, although they actually received a payout during the redistribution process. As a result, smallholder farmers, having no proper documents, cannot expand irrigation on their 100 ha of land as they are barred by the general authorization from exceeding the mandated volume of water and at the same time are unable to obtain water-use licenses.

The politics of water and land rights in South Africa is explained by van Koppen et al. (2009) who state that during the government land reform program there was initially little cooperation between the then Department of Land Affairs (now Department of Rural Development and Land Reform) and the Department of Water Affairs and Forestry (DWAF) (now Department of Water and Sanitation). This resulted in cases where water rights tied to lands under claim were sold, reducing the value of the land. Without readily available registers of land claims, DWAF could not easily track this problem; so a policy was introduced stating that trading of water rights of land under claim should not be approved. It was only in 2008 that effective coordination was established between DWAF, the provincial Departments of Agriculture and the provincial governments of South Africa with the signing of a memorandum of understanding on collaboration on land and water reform.

Visioning Exercise

The visioning exercise conducted as part of this study was an opportunity for the community to look at the future of their farming and develop ideas of what they would like it to be, considering the current challenges. According to Chitakira et al. (2012), collective visioning builds capacity, encourages ownership and creates opportunities for the community to collaborate in developing shared priorities. We conducted a participatory visioning exercise in each of the three communities (Prieska, Mahale and Ga-Selwane) along the Great Letaba River to identify:

(1) the main challenges affecting their agriculture and livelihoods;

(2) the main elements of their vision for their agriculture and livelihoods; and

(3) the role of sustainable farming and improved crop management practices in achieving that vision.

The farmers shared common elements and aspirations that are at the core of their vision. Based on the currently experienced challenges, a common vision with specific elements was developed for the communities.

As a background to the visioning process, participants discussed the main challenges faced by the community's agriculture. Major concerns about yields and river flows were identified (Figure 9). There were no concerns unique to a particular community. From all the three communities' perspectives, a flourishing future was foreseen based on improving the governance of the land tenure system in the area, and improved water-saving techniques, which are currently the major constraints to enhancing crop yield and quality. From our discussions with the local communities, it was evident that they mostly rely on access to productive land and water as natural resources for their livelihood. However, land tenure reforms have been marred by governance challenges that have let down agriculture as a livelihood in these communities. Adams et al. (1999) explain that good governance is important for the reform of land tenure, especially for communities where the main source of livelihood is pursued on land and that uncertainty makes land use for livelihoods too risky. There have been inadequacies of land tenure administration and governance which have resulted in a land ownership dilemma subsequently affecting water licensing. None of the smallholder farmers interviewed had water-use licenses, as they do not have proof of land ownership to allow them to apply for licenses and expand farming beyond 20 ha.

The farmers also recognized that sustainable management of land and water resources is important to improve crop yield and quality. According to the communities, the area's climatic conditions are varied and have changed over the years with more droughts being experienced, leading to compromised crop yield and quality.

As a result of droughts, the Great Letaba area has a high evaporation rate and, frequently, reduced river flows, which means less water is available for irrigation. Since the farmers use small pumps, less water can be lifted to the farm during times of low flow. In times of drought, some crops mature faster than normal or have stunted development, which compromises their quality. According to the farmers, most droughts have hit at the worst time of crop development, i.e., the flowering stage, during which the crop becomes heat stressed at temperatures above 30°C, which can compromise crop quality and ultimately lead to low yield. Most of the farmers do not practise any sustainable-agriculture or water-saving techniques such as mulching and erecting shade nets to retain soil moisture. FAO (2017) explains that sustainable water-use techniques are powerful triggers for improvement of crop yield.

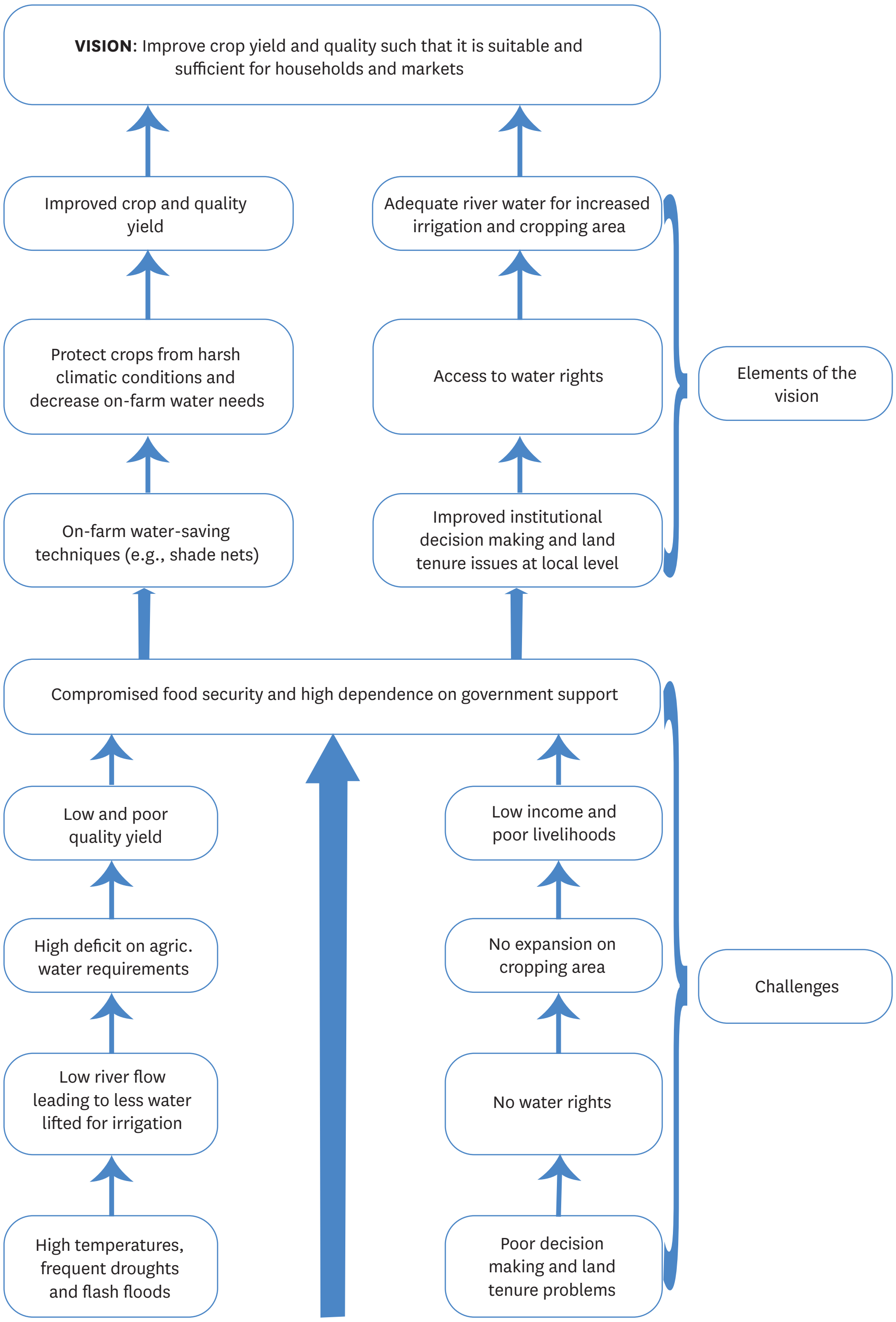

Figure 9. Output from the visioning exercise conducted with participants.

Based on these challenges and concerns, the participants explained their vision for the future. Women participants mostly desired increased crop yield for the food security of their households. The men mostly desired increased crop yield and quality to meet market demands and requirements. From these, the overall community vision was to "improve crop yield and quality such that it is suitable and sufficient for households and markets" (Figure 9). Participants also discussed the time period over which this vision could be achieved. Most participants' time frame ranged from 1 to 3 years. None of the participants opted for a longer period, reflecting the urgent need to achieve the desired vision.

Implications of this Chapter

In our community interviews and discussions, there was consensus that the Great Letaba River area is largely arid with very low mean annual rainfall and a high evaporation rate. Farmers had their worst season during the period 2016-2018 due to higher temperatures and drought, which resulted in the lowest yields experienced by these farmers. Groundwater was depleted, which increased pumping. The extreme temperatures and low rainfall resulted in field crops wilting as the water demand intensified. While access to water for crop irrigation has been hampered by low river flows in the past six years, flash floods are common in this area. Water for irrigation is limited as the water depth has decreased, and the river dries out quickly. Drought-tolerant crops are now preferred here, e.g., okra, beans, chili, onion and cowpea. Poor quality crops and yields have been experienced over the past five years. Most farmers regarded the 1999/2000 season as their best season with constant river flows, fewer flash floods, higher and good-quality yields. Minimal crop and water-saving techniques are practised in the Great Letaba River area. Based on the communities' perception, all ecosystem services have been affected by changes in the river flows as reduction in flow affects how much water is available for irrigation, livestock farming, fishing and spiritual occasions.

This work has been carried with limitations. Where working in groups was not permitted because of the Covid-19 risk, individual interviews were conducted instead of focus group discussions. Some farmers and community members refused to be part of the study as they feared the risk of infection from 'outsiders'. Our plan was to use maps to identify the areas where ecosystem services are accessed. However, as most of the participants were not literate, it was not possible for them to use maps. So, the idea of using maps had to be dropped to reduce the risk of Covid infection. Instead, field tracking with some participants was used to physically identify areas along the river where they derive some ecosystem services.

Modeling the Contribution of E-Flows to Sustainable Agriculture, Food Security and Livelihoods

The livelihoods of many smallholder farmers in the Limpopo Basin are dependent on abstracting irrigation water from rivers. Access to river water strongly reduces the risk of drought-induced production failure, especially during the dry season, when purely rainfed agriculture is unviable. Not only does the overuse of river water by commercial agriculture and other users jeopardize environmental outcomes, it also threatens smallholder farmers. Flow gauges in many rivers of the Limpopo Basin record considerable periods of zero flow, in downstream sections in particular, where both the environment and smallholder farming communities are then unable to meet their needs.

E-flows include the water provided within a river or wetland to maintain aquatic ecosystems and serve basic human needs. Importantly, e-flows represent the amount of water that must remain in the river to sustain it before all flows in excess of the e-flows are allocated and used. Consider also that in South Africa, apart from the Ecological Reserve (e-flows) and basic human needs (25 liters per person per day), only international obligations are rightful restrictions that can be held or protected by the government. All other flows, which include flows required for subsistence agriculture, are allocable for use through equitable sharing processes. But they must still be approved following these processes by the Department of Water and Sanitation. The mechanism established to support this process in South Africa is the 'Source Directed Control' section of the National Water Act (NWA 1998). While the benefits of policies that enforce e-flows may be obvious, the implications of such policies for smallholder farmers are much less clear. Since e-flows do not consider subsistence water use by local communities, these requirements are considered to be competing with e-flows. Many stakeholders believe that there is some form of a necessary trade-off between using water for subsistence agriculture and guaranteeing environmentally required flow levels in rivers. While this interpretation likely holds true for commercial farmers, whose water abstraction activities may be curtailed in order to meet e-flow requirements, the impact of meeting e-flows potentially at the expense of subsistence farmers is likely to depend on how exactly e-flow levels are determined and how e-flow policies are implemented.

In reality, communities have been tapping into the e-flow provision for rivers, including the Great Letaba River, to provide water for their subsistence agriculture needs as well as for large-scale agriculture, without consideration of the requirements of the river. While the subsistence withdrawals may be perceived to be included in the 'basic human needs' part of the reserve, such abstractions, if large enough, are detrimental to rivers and result in insufficient flows remaining in the rivers to sustain them. With a focus on environmental sustainability, and without distinction between commercial and subsistence farms, water allocation policies in the region run the risk of threatening the livelihoods of subsistence agriculture farmers. While some trade-offs may be unavoidable, forward-thinking water resource management policies aligned to e-flow policies should be established that consider both environmental and human livelihoods, including subsistence agriculture, which is a critical requirement for these communities to become sustainable. By characterizing and prioritizing the needs of subsistence agriculture in water resource management and aligning them with e-flow and international obligations, there is a possibility that ecosystems as well as the livelihoods of the vulnerable human communities who depend on these resources can be sustained. During drought periods or in times of water scarcity in the river, such policies would impose restrictions on water use for commercial agriculture and other users (such as industry), while allowing smallholder farmers to keep abstracting water for irrigating their subsistence agriculture plots. An important question in implementing regional water resource management policies is whether watershed management authorities see their role solely as one of restricting excessive use, or whether they are willing to actively bolster river flows through dam releases or similar measures for water security. This is not suggested to be a uniformly beneficial approach to regional water resource management, particularly in areas where dam construction and operation would reduce the existing condition of water resources through barrier formation and water reduction associated with the purpose of the dam. In such scenarios, gazetted water resource management policies or decisions should be formalized to include environmental (e-flows) and subsistence agriculture requirements as prioritized use that may support both outcome dimensions, at least as long as sufficient water resources can be mobilized upstream.

The first stage of linking e-flows to agriculture included the development of a conceptual impact pathway model, as shown in Figure 10, that describes the current state of knowledge about the expected influence of the intervention on the system outcomes of interest. In this case, the intervention was related to the different possible options for e-flows, and the outcome of interest was the impact on smallholder farmers' livelihoods.

Results of Modeling E-Flows

Natural Flows, Present Flows and E-Flows

For the scenarios considered in this section of the study, natural flows, present flows and e-flows at the 50th and 5th percentiles, which respectively represent the base flows and extreme low flows, were considered. The graphs in Figures 11 and 12 show that present flows are substantially lower than natural flows.

These graphs are based on an analysis of the long-term natural flow, present flow and e-flow time series at the 50th percentile, which represents the base flow, and the 5th percentile, which represents the extreme low flow. It is acknowledged that flows in the Great Letaba River, like the rest of the Limpopo River mainstem and its tributaries, have been altered because of the construction of numerous dams and irrigation and urban abstractions. Thus, the observed flows from the selected gauging weir might not provide reference/natural-state information. However, it does provide some indication of the flows in the present state when sampling was undertaken.

The following sections describe the results of the modeled scenarios.

Crop Water Need

Crops grown by subsistence farmers in the target communities were estimated to require approximately 2 Mm^3/a of water with up to 4 Mm^3/a within the range of possible values (Figure 13). Water demand by crops was unevenly distributed over the months of the year, with lower need during the cooler months and peak demand between September and January (Figure 14).

To meet the water requirement of their crops, farmers were estimated to require an amount of irrigation water that corresponded roughly to the total water demand of the crops (Figure 15). While this might seem surprising at first glance, this high demand derives from inefficiencies in the irrigation system, within which only about 50% of water pumped from the river was expected to contribute to crop growth.

Mirroring the water demand by crops, irrigation water need was also found to vary throughout the year, with the highest demand diagnosed for the months of September through December (Figure 16).

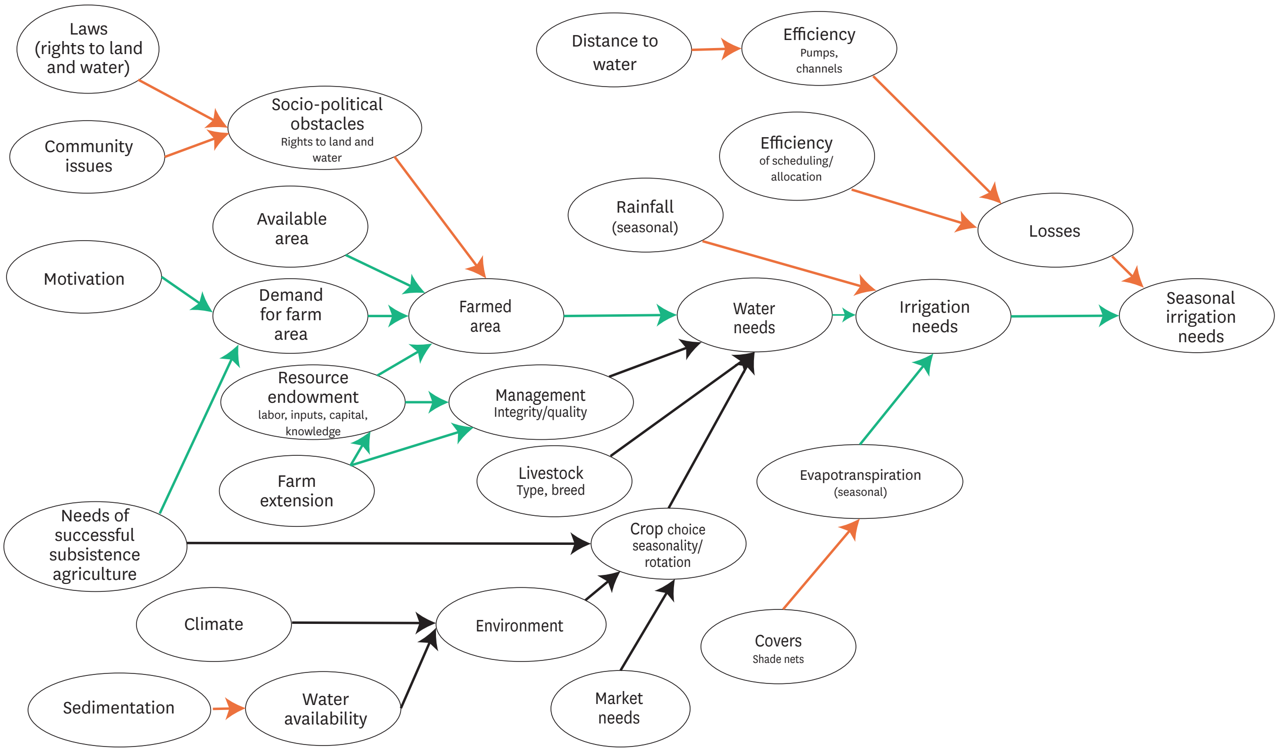

Figure 10. A conceptual model of the social effects of altered river flows on the sustainability of livelihoods in the Limpopo Basin.

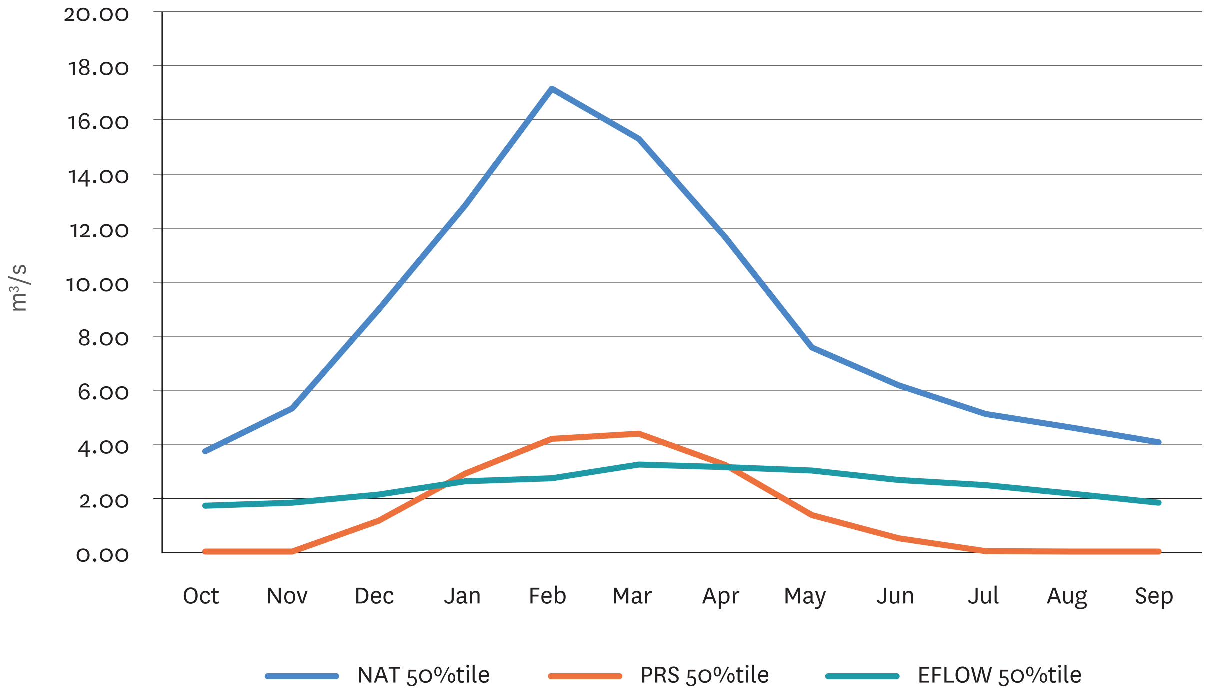

Figure 11. Graph showing the 50th percentile of the natural flow (NAT), present flow (PRS) and e-flow (EFLOW), which represent the base flows at the site GLET-B81J-LRANC.

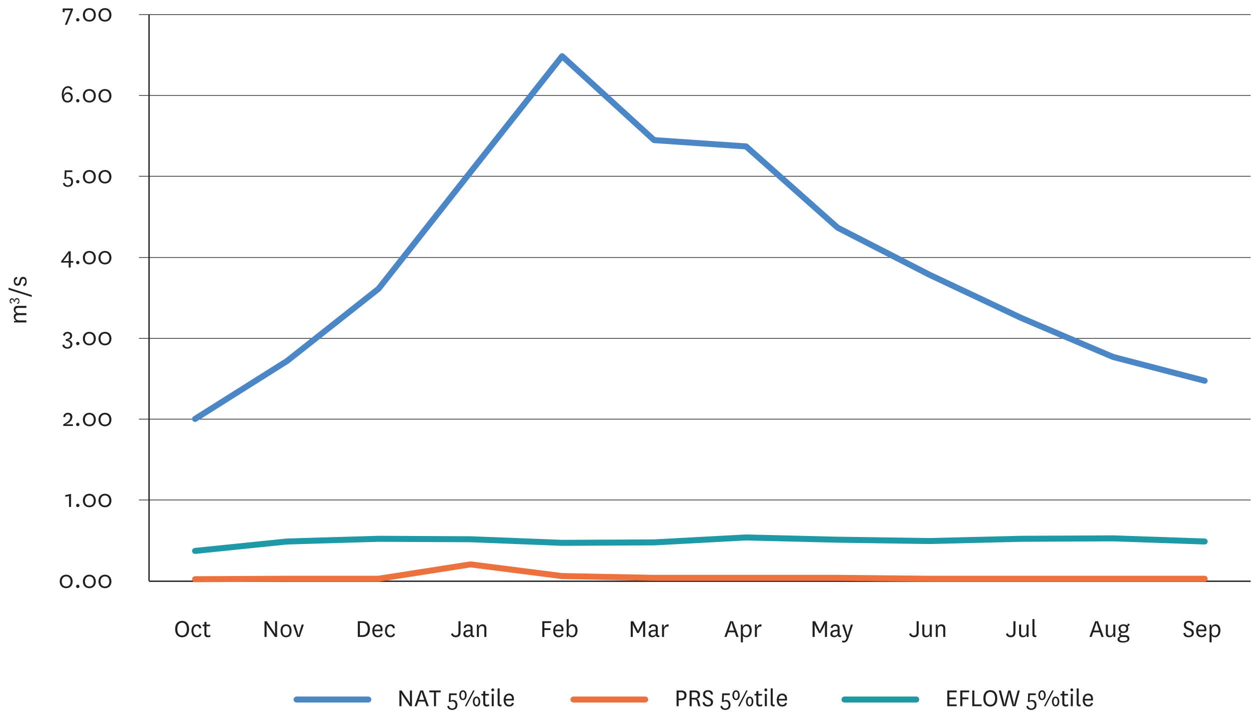

Figure 12. Graph showing the 5th percentile of natural flow (NAT), present flow (PRS) and e-flow (EFLOW), representing the extreme low flow at the site GLET-B81J-LRANC.

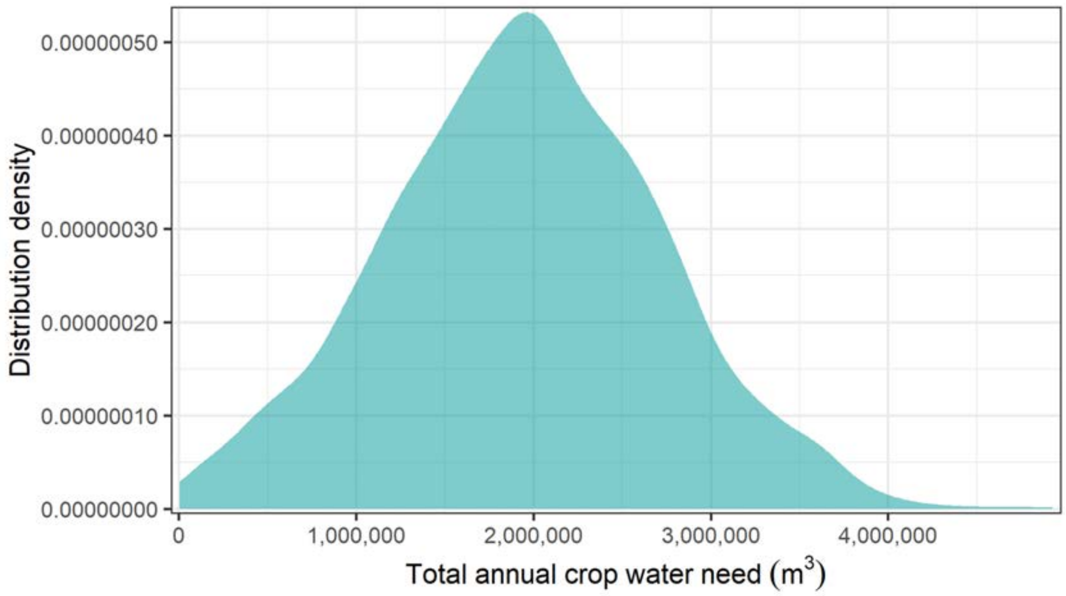

Figure 13. Annual crop water need of subsistence farmers in the target communities, according to a Monte Carlo simulation with 2,900 model runs. The model runs were based on hydrologic conditions during 29 historic years, with each year used for 100 runs. Non-hydrologic variables were estimated as probability distributions of plausible values based on expert assessment.

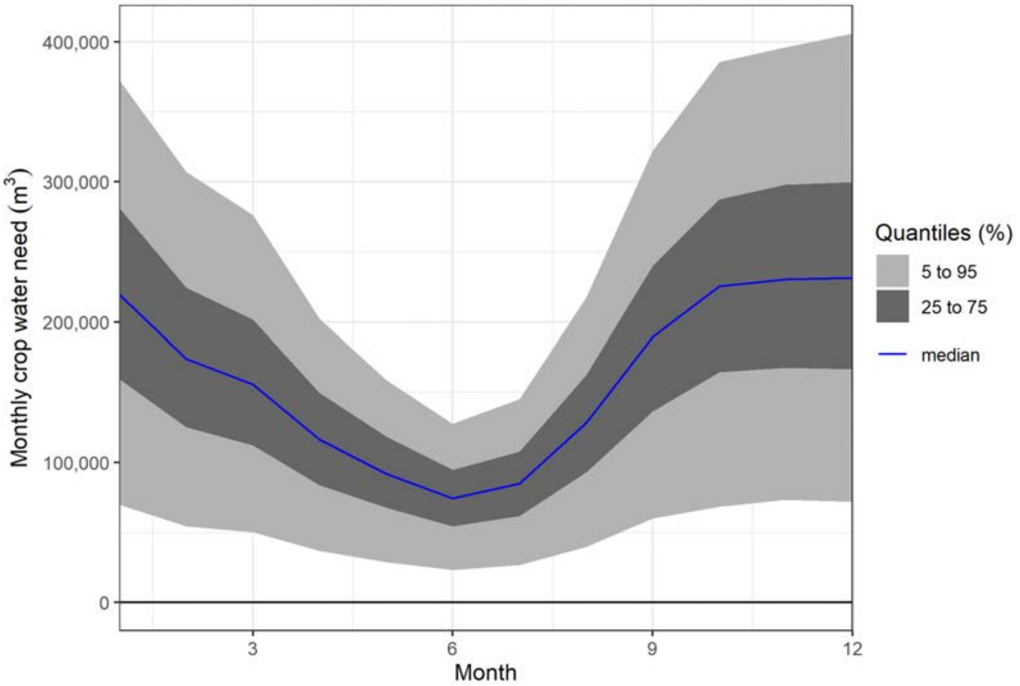

Figure 14. Monthly crop water need of subsistence farmers in the target communities, based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

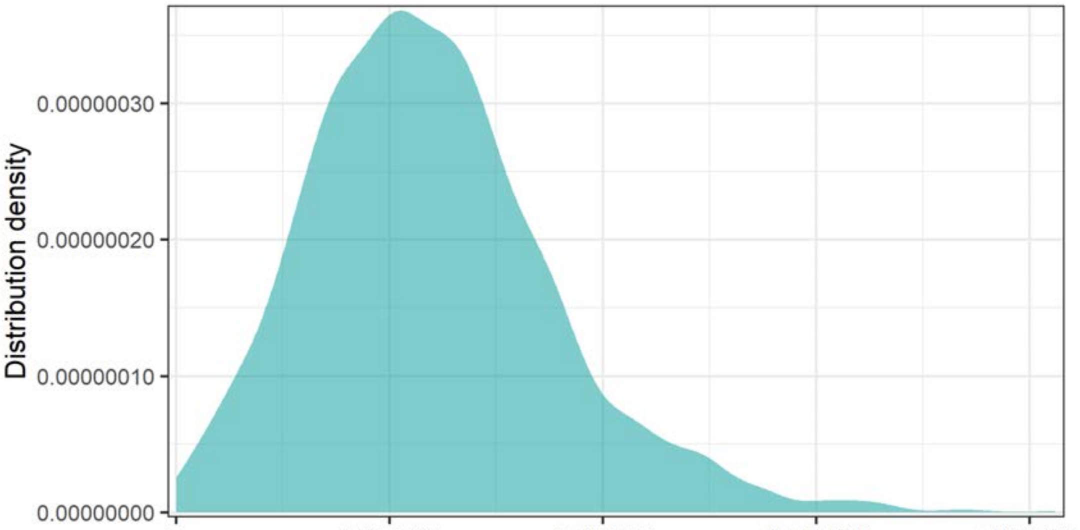

Figure 15. Annual irrigation water need in the target communities, according to a Monte Carlo simulation with 2,900 model runs. The model runs were based on hydrologic conditions during 29 historic years, with each year used for 100 runs. Non-hydrologic variables were estimated as probability distributions of plausible values based on expert assessment.

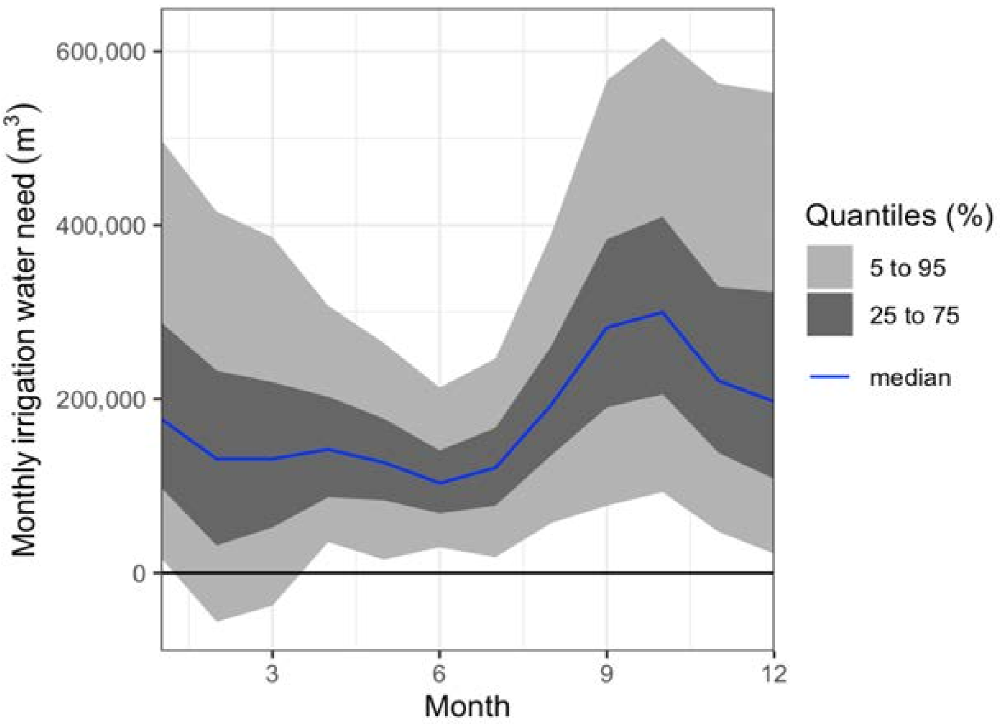

Figure 16. Monthly irrigation water need, based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

Crop Water Gap and Downstream River Flow

The crop water gap has been defined as the relative shortfall of available water compared to the overall water demand of agricultural crops. Thus, in the presentation of the results below, the crop water gap is shown as a percentage of the irrigation water needed. The greater the percentage, the greater the shortfall in supply of irrigation water.

Unrestricted Baseline Scenario (UNRES)

For the UNRES scenario, i.e., for unrestricted water extraction in the absence of an e-flow policy, the model identified a considerable shortfall of irrigation water supply in almost all the simulated years (Figure 17). The demand of year-round crop production could only be met in about 1% of the years, whereas in about a quarter of the years, more than half of the required irrigation water was unavailable, with peak shortfalls of up to 80%.

Water shortfalls were unevenly distributed across the months of the year, with predictably greater shortfalls during the dry season between July and November when high crop water demand coincides with low river flow volumes (Figure 18). Importantly, this period of risk to subsistence farmers coincides with the onset of spring and early summer when flows begin to increase in the river due to rainfall but the general demand for water on a regional scale is greatest. During this period of spring and early summer, historically when the river was in a better ecological condition, communities would have access to other provisioning services from the river including plants and fish. Under present conditions, these services are reduced, which exacerbates the impact of reduced flows on agricultural crop growing and affects the livelihoods of communities.

The need to implement a mechanism for maintaining e-flows is clearly demonstrated by the very low flow volumes downstream of the target communities in all but the wettest months of the year (Figure 19).

Risk of Reduced Flows Associated with Providing E-Flows Alone (EFLOW Scenario)

Compared to the baseline scenario, prioritizing environmental e-flows (EFLOW scenario) substantially exacerbates water shortages for smallholder farmers (Figure 20). The increase in the crop water gap ranged from zero to more than 60 percentage points, with almost 80% of the model runs showing water gap increases by up to one-fifth of the overall crop water demand.

The change in the water gap in the EFLOW scenario reached up to 80 percentage points in some years during the months of January, April, June and July, but also amounted to zero in more than half of all model runs (Figure 21).

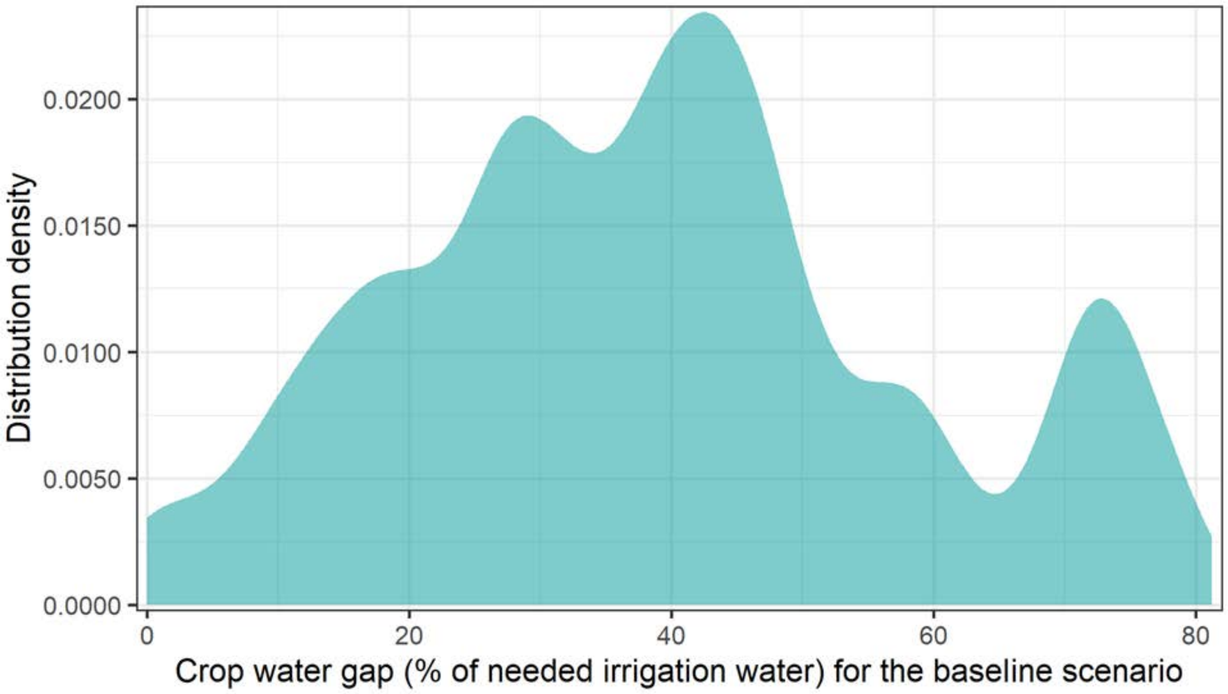

Figure 17. Probability distribution of the crop water gap for the UNRES (unrestricted) baseline scenario (no e-flow policy). The model runs were based on hydrologic conditions during 29 historic years, with each year used for 100 runs. Non-hydrologic variables were estimated as probability distributions of plausible values based on expert assessment.

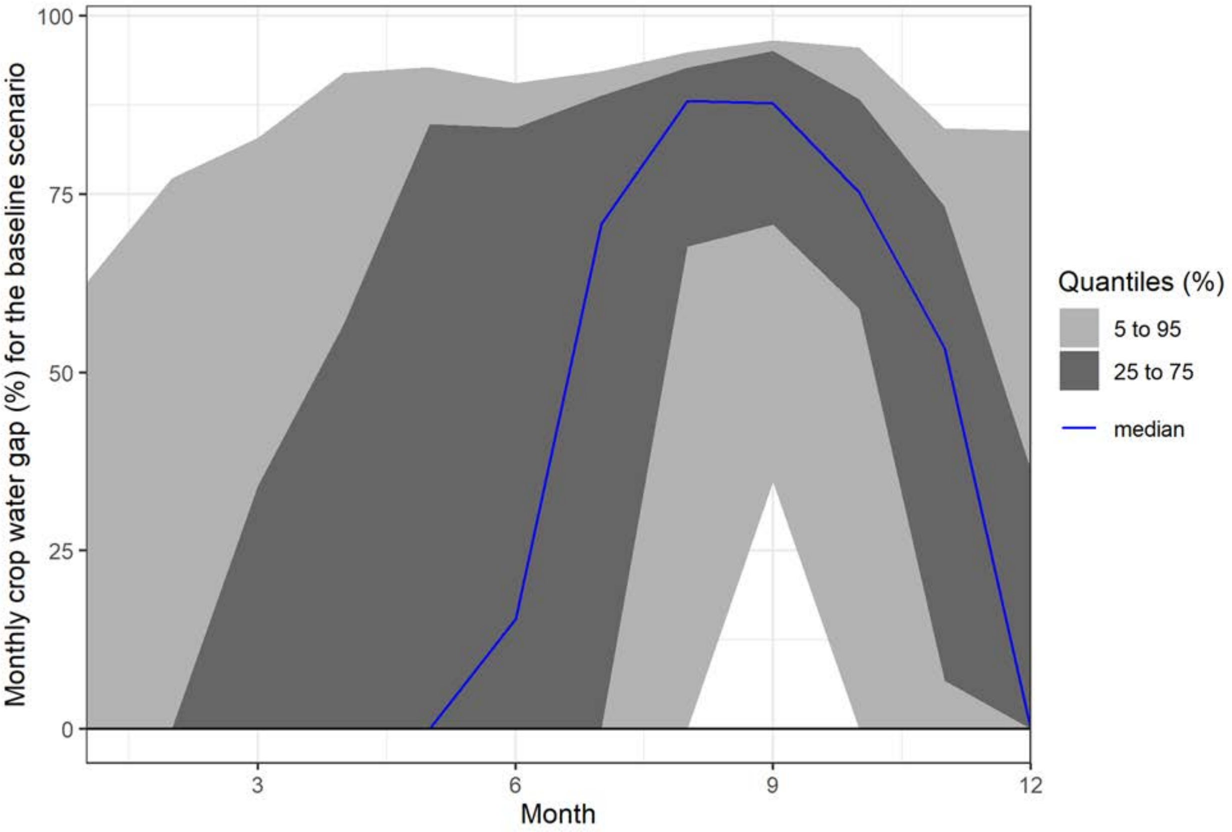

Figure 18. The crop water gap for the UNRES baseline scenario throughout the year, based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

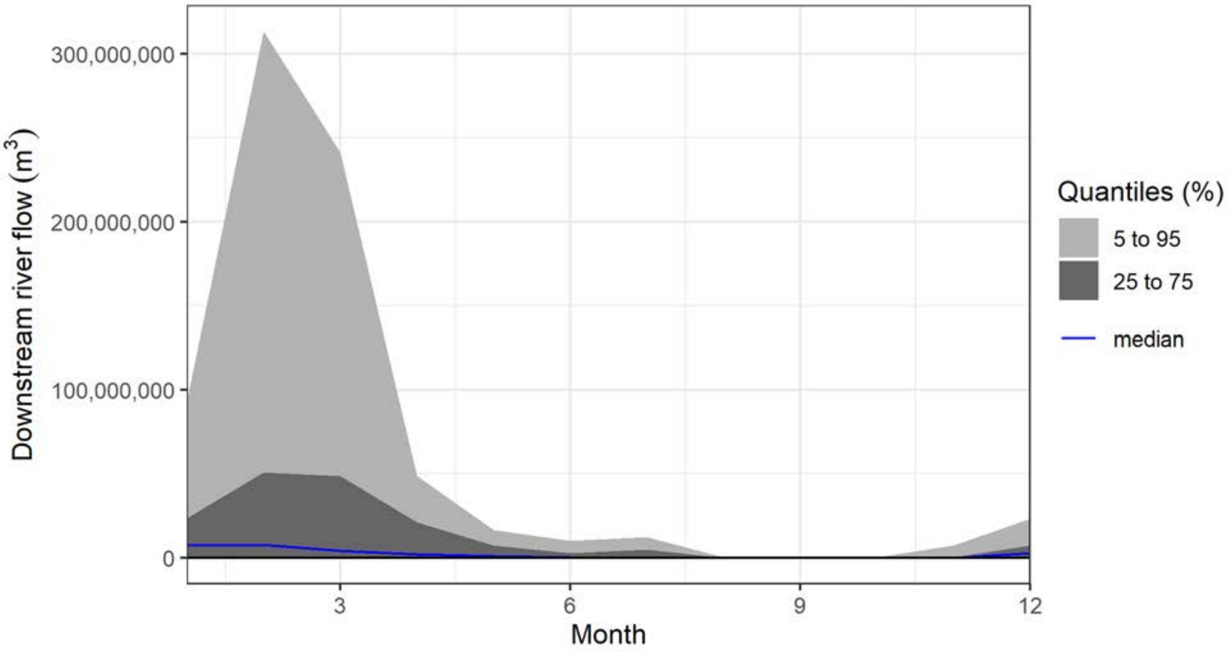

Figure 19. Downstream river flow volumes for the UNRES (unrestricted) baseline scenario, based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

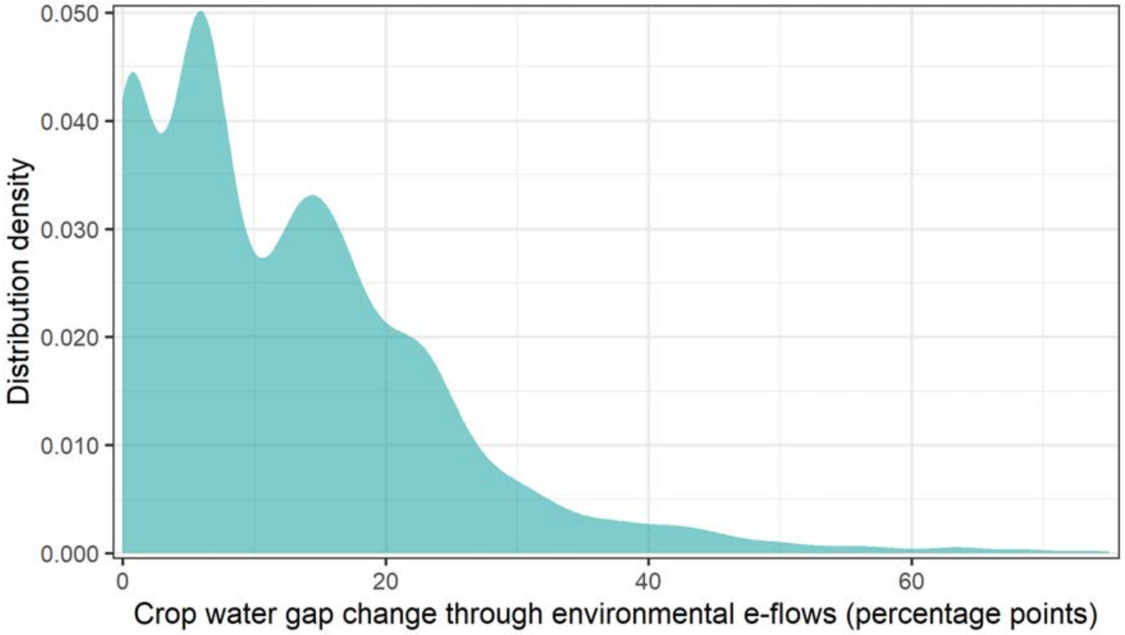

Figure 20. Average change in the crop water gap over the months of the year caused by the implementation of a purely environmentally focused e-flow policy (EFLOW scenario). The model runs were based on hydrologic conditions during 29 historic years, with each year used for 100 runs. Non-hydrologic variables were estimated as probability distributions of plausible values based on expert assessment.

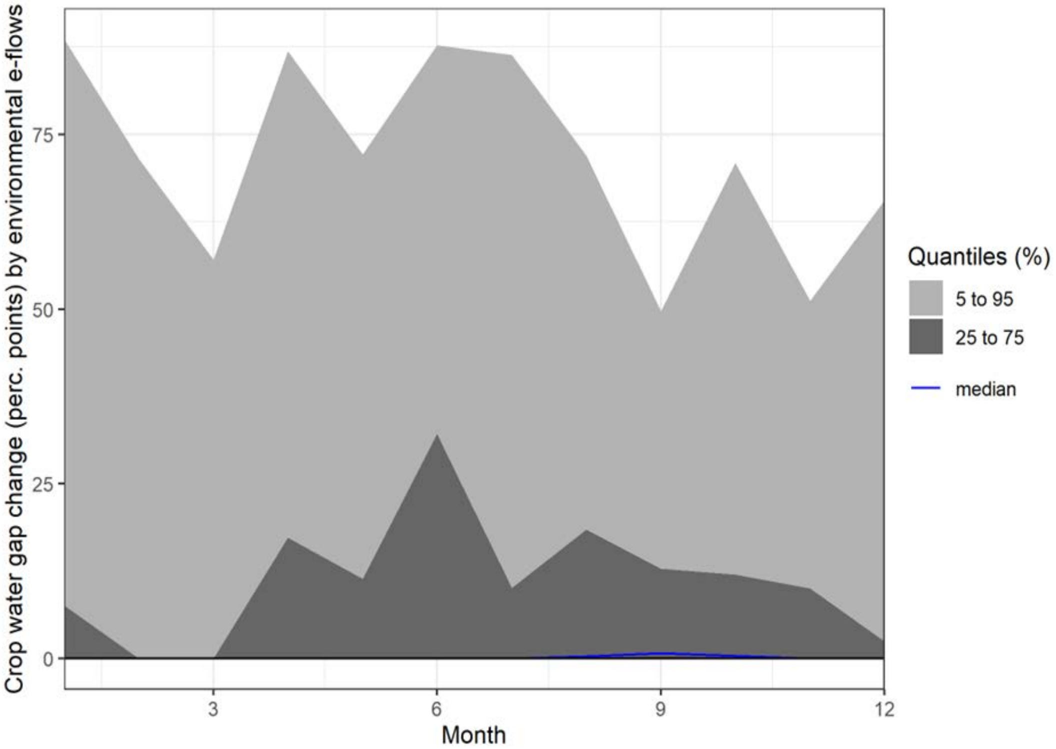

Figure 21. Increase in the crop water gap for subsistence farmers under a purely environmentally focused e-flow policy (EFLOW scenario), based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

Predictably, a purely environmentally focused e-flow policy showed positive effects on downstream river flows in many years of the simulation (Figure 22). However, it is worth noting that in most years, there was no such effect in any month (indicated by the median line coinciding with the x-axis. Given the low downstream levels in the absence of any e-flow policies, that is in the UNRES scenario (Figure 19), this implies that in the absence of any measures to actively raise river flow volumes in times of water scarcity, such a policy may fail to fully meet environmental objectives.

Risk of Reduced Flows Associated with Supplementation of E-Flows and Flows Required for Subsistence Agriculture (SUPPL Scenario)

Compared to the UNRES baseline scenario, the crop water gap is greatly reduced in the SUPPL scenario (Figure 23) in which irrigation water shortfalls are prevented through dam releases or other water additions upstream so that the crop water gap is effectively zero in all months of the year.

To mobilize sufficient water for implementing the livelihoods e-flow (SUPPL) scenario, substantial water releases from dams or other supplementary water sources are needed upstream (Figure 24). In many years, releases are needed during all months of the year, which is probably an unrealistic expectation.

If the required water releases can be mobilized, or the required flows can be ensured by restricting upstream water use, e.g., by commercial farms, river flow volumes during the dry months would strongly increase in all years. Even during the humid months, a sizeable proportion of simulated years included such increases (Figure 25).

Sensitivity Analysis

We used sensitivity analysis to rank the modeled variables in the order of their importance to the outcomes of interest for each of the three modeled scenarios. These results show the importance of individual variables in the form of a VIP score as well as the direction of the relationship (negative or positive coefficient) (see Figure 26).

The sensitivity analysis of crop water need for subsistence farming showed that the number of subsistence farmers in the area was the most defining factor, followed by the area available for irrigated agriculture (Figure 26). Other important variables were the share of land that was unused for social or political reasons, and the farm area needed by subsistence households. While we had considerable uncertainty about these variables when running the model, it should be possible to obtain more precise information through a detailed field survey.

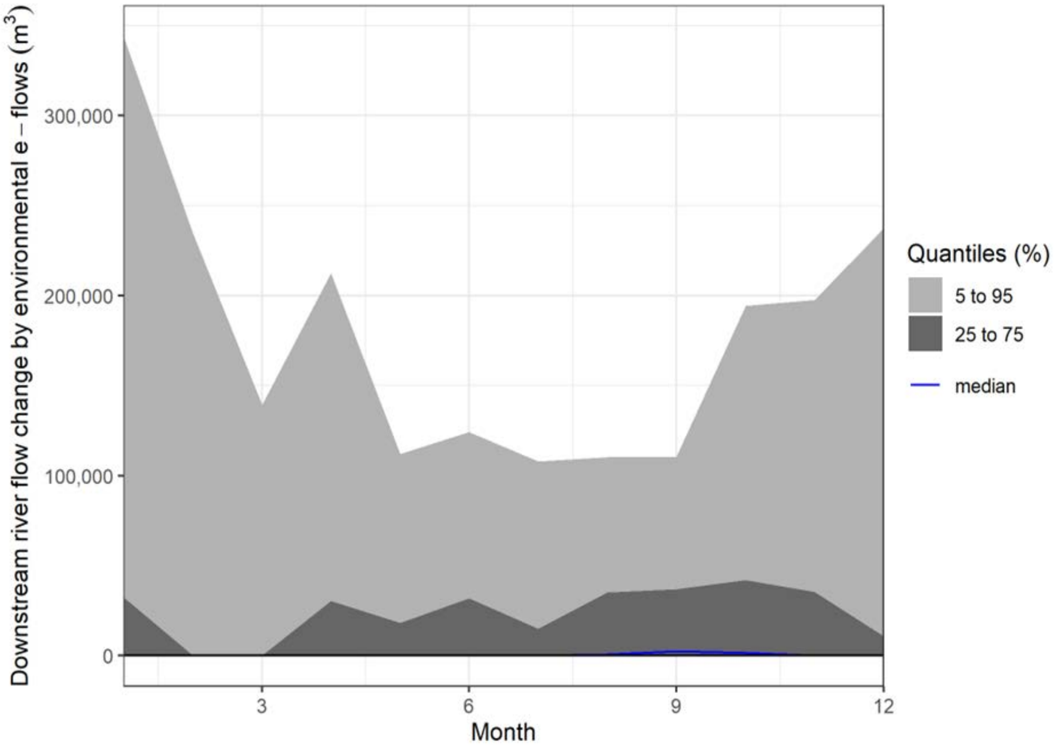

Figure 22. Increase in downstream river flow caused by a purely environmentally focused e-flow policy (EFLOW scenario), based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

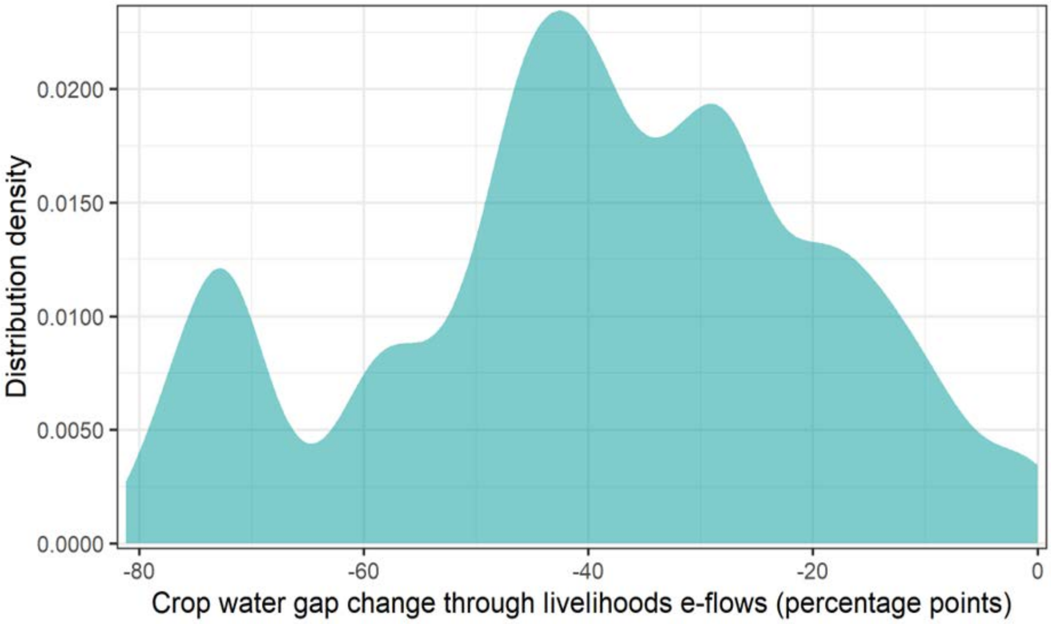

Figure 23. Change in the crop water gap for the livelihoods e-flow scenario (SUPPL) compared to the baseline. The result of this change is a complete elimination of the crop water gap. Model runs were based on hydrologic conditions during 29 historic years, with each year used for 100 runs. Non-hydrologic variables were estimated as probability distributions of plausible values based on expert assessment.

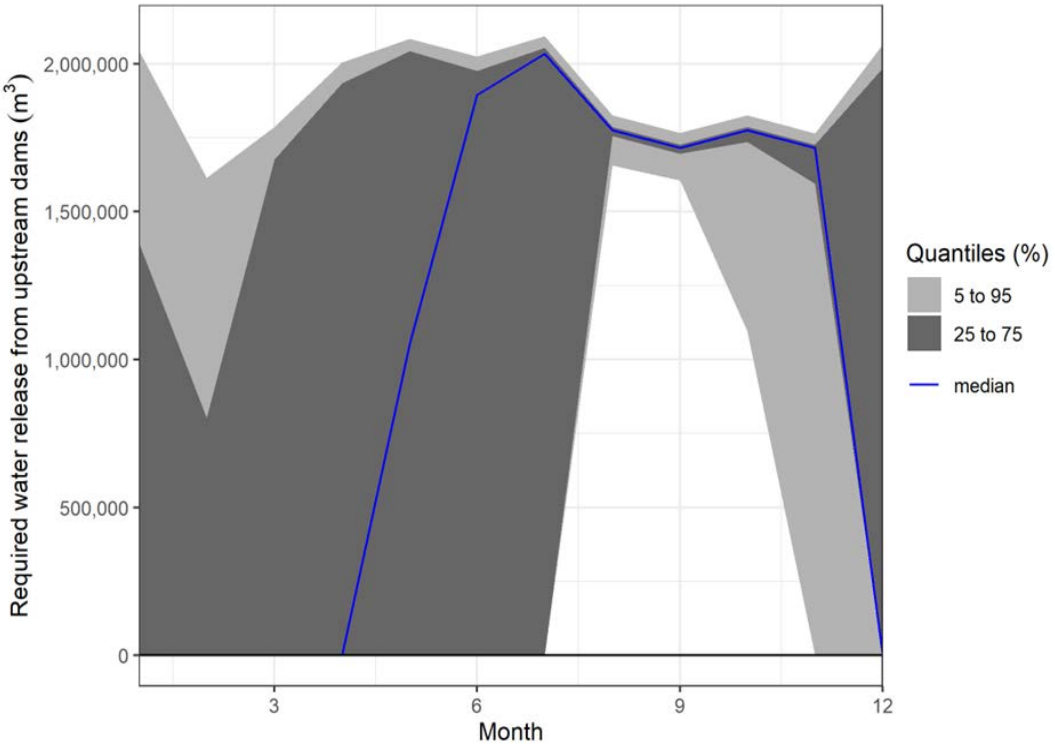

Figure 24. Required water releases from upstream dams for the maintenance of livelihood e-flows (SUPPL scenario), based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

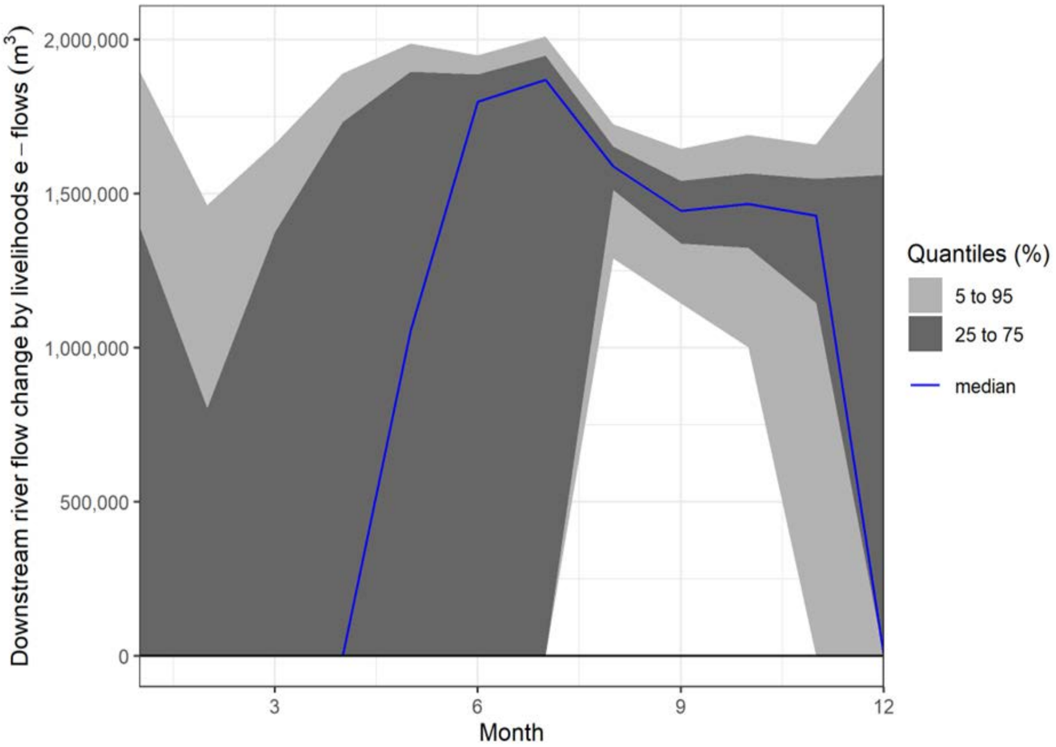

Figure 25. Downstream river flows below the target communities in the livelihoods e-flow (SUPPL) scenario, which includes dam releases to reach the required e-flow levels, based on a Monte Carlo simulation with 2,900 model runs (29 historic years, each repeated 100 times). The shaded areas illustrate the 50% and 90% confidence intervals of the distribution, with the blue line showing the median.

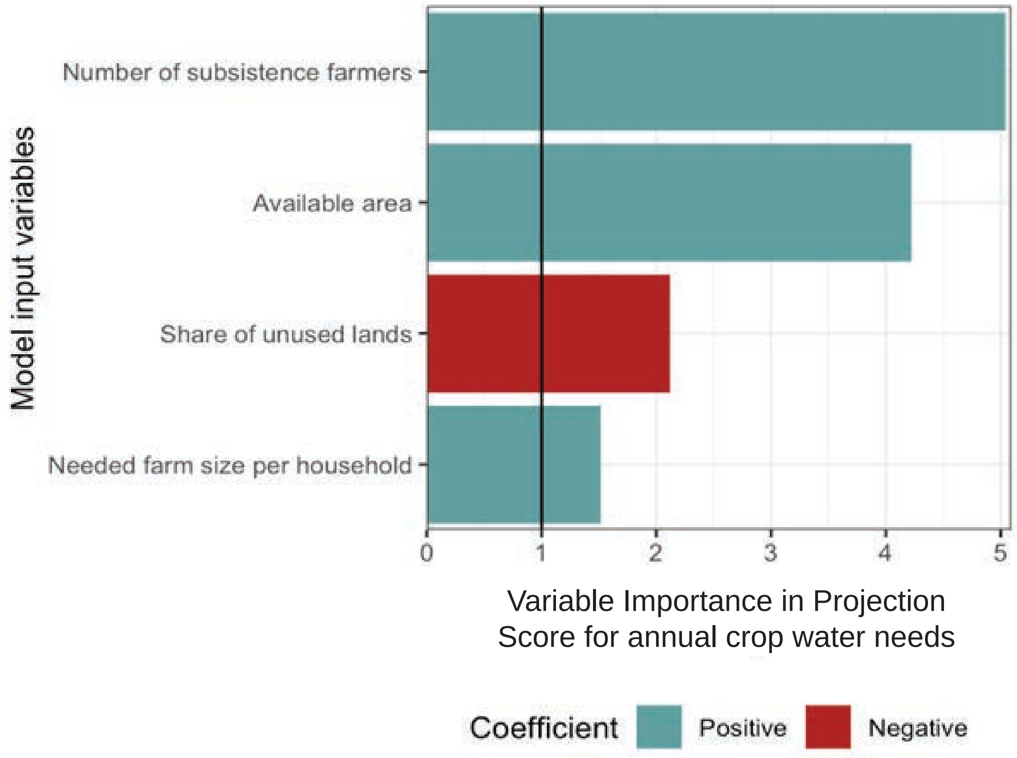

Figure 26. Sensitivity analysis of the crop water need for subsistence farming based on Partial Least Squares (PLS) regression. Sensitivity was estimated by constructing a PLS model relating variation in model outputs to variation in all input variables. The VIP score is illustrated as a measure of variable influence.

Irrigation water need depended on considerably more factors (Figure 27), including several farm-related variables. In addition to variables that were also related to crop water demand, many variables linked to evapotranspiration, rainfall and river flow emerged as important. The efficiency of irrigation scheduling as well as the efficiency of water pumps also appeared in the list of important variables.

The crop water gap in the UNRES baseline scenario was most sensitive to uncertainty about river flow levels, with flows in May, July, September, June and January showing the strongest effect (Figure 28). Further drivers of the crop water gap were the reference evapotranspiration and precipitation in February. Several more variables were identified as important, all of which were river flow levels, precipitation or evapotranspiration in certain months. No uncertainties related to other system features were identified as important.

For the EFLOW scenario, the set of influential variables was quite similar to the UNRES baseline scenario, with only monthly river flow, reference evapotranspiration and precipitation being among the important variables (Figure 29).

For the livelihoods e-flow SUPPL scenario, the crop water gap was reduced to zero by definition; so a sensitivity analysis would not produce interesting results. A more relevant model output variable to analyze in this scenario is the annual requirement of additional river flow from dam releases or other sources (Figure 30), which only showed a strong response to hydrologic variables related to river flow, evapotranspiration and precipitation.

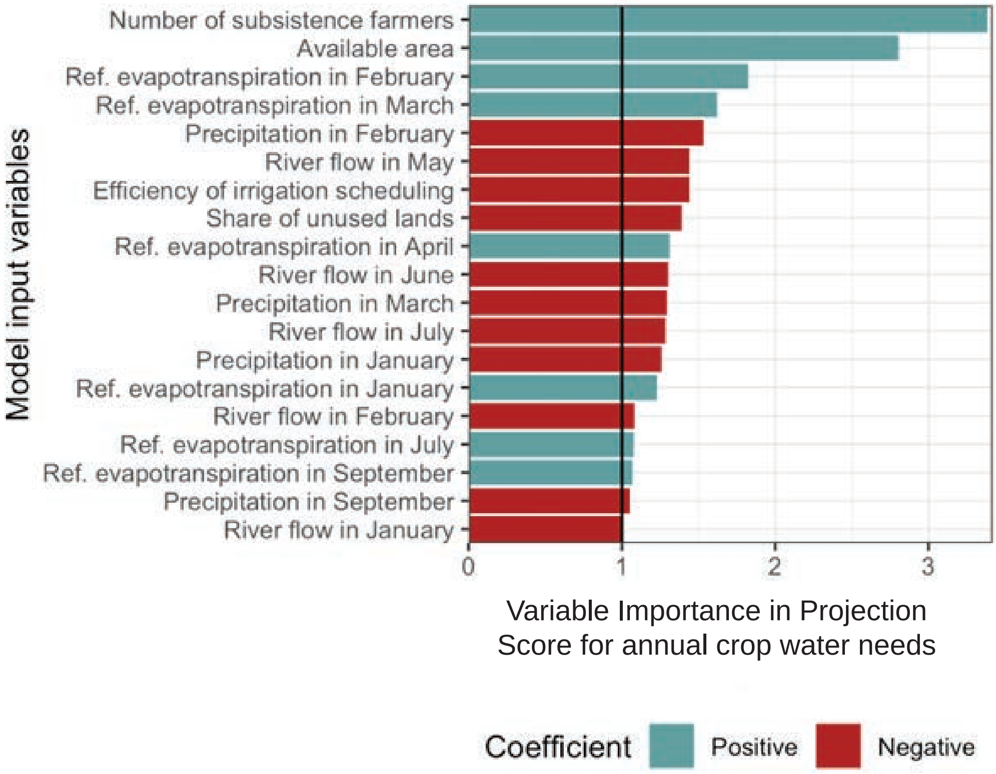

Figure 27. Sensitivity analysis of the irrigation water need for subsistence farming based on PLS regression. Sensitivity was estimated by constructing a PLS model relating variation in model outputs to variation in all input variables. The VIP score is illustrated as a measure of variable influence.

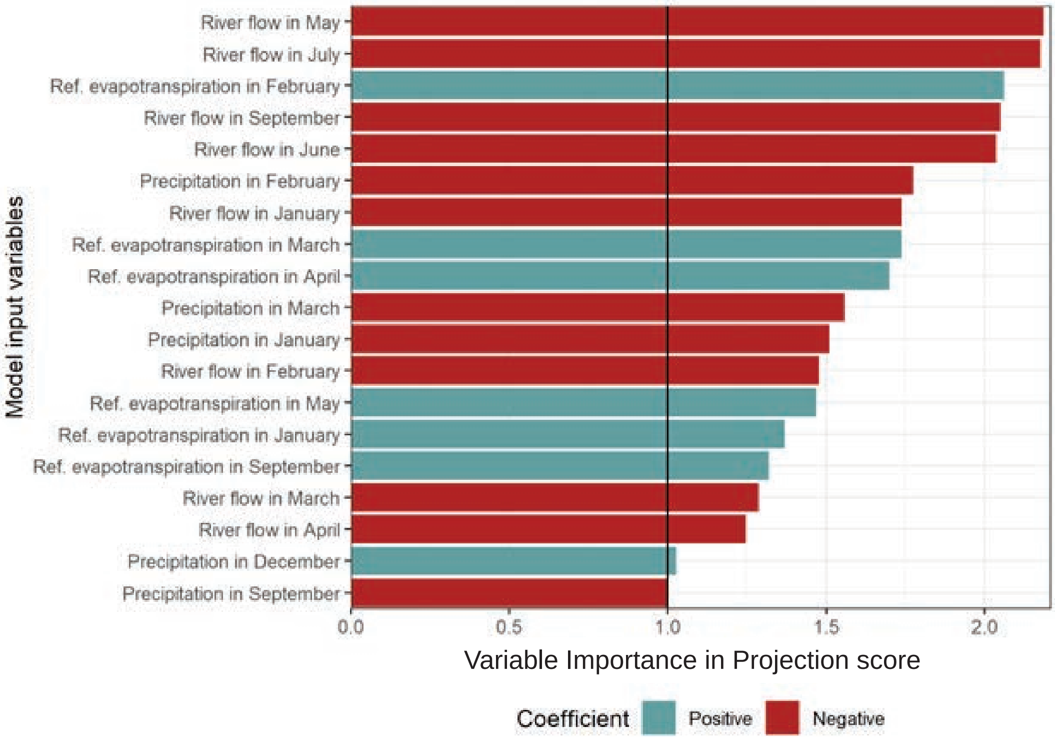

Figure 28. Sensitivity analysis of the crop water gap for the UNRES baseline scenario based on PLS regression. Sensitivity was estimated by constructing a PLS model relating variation in model outputs to variation in all input variables. The VIP score is illustrated as a measure of variable influence.

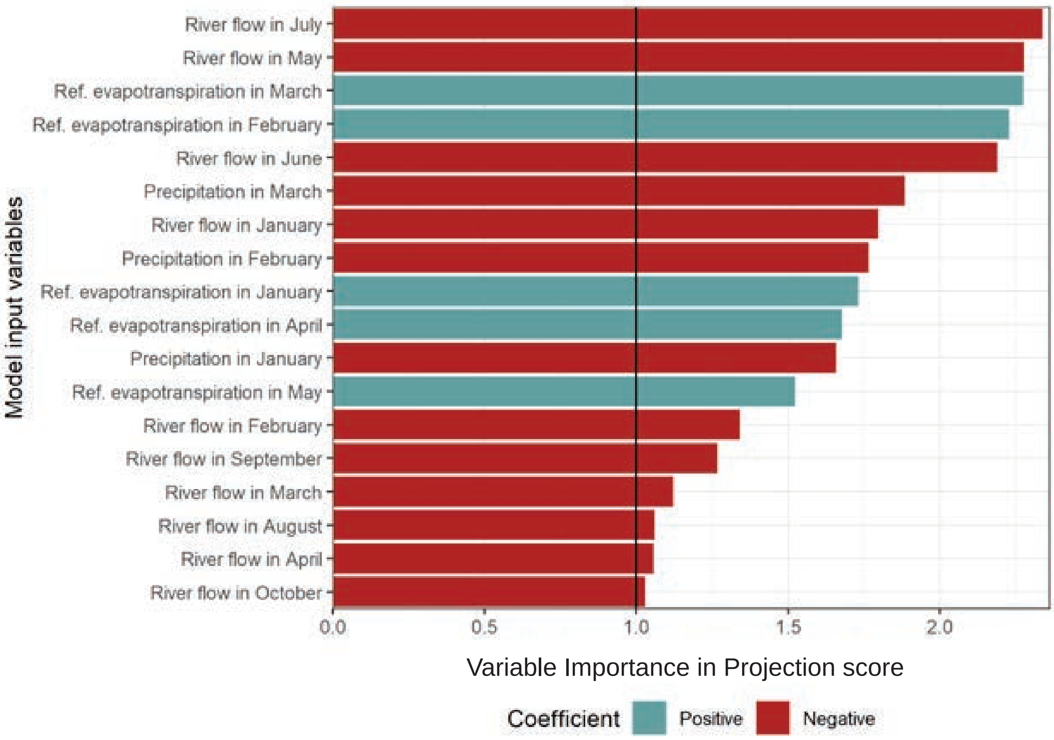

Figure 29. Sensitivity analysis of the crop water gap for the EFLOW scenario based on PLS regression. Sensitivity was estimated by constructing a PLS model relating variation in model outputs to variation in all input variables. The VIP score is illustrated as a measure of variable influence.

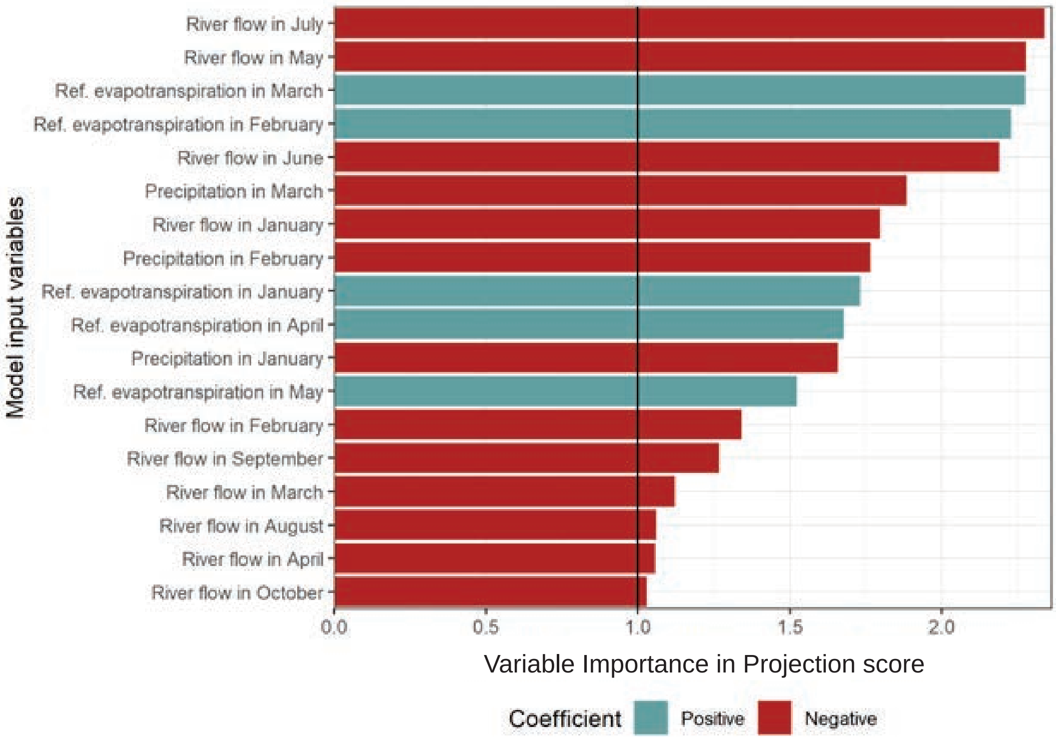

Figure 30. Sensitivity analysis of required dam releases (or other additional sources of water) for the livelihoods e-flow (SUPPL) scenario based on PLS regression. Sensitivity was estimated by constructing a PLS model relating variation in model outputs to variation in all input variables. The VIP score is illustrated as a measure of variable influence.

Discussion of the Simulation Results

The results of our simulation clearly indicate that subsistence farmers in the target communities often suffer from a severe shortage of water to meet their subsistence agriculture farming needs. This probably constitutes a strong limitation for irrigated agriculture, in particular during the dry season. Given the present scarcity of water in the Great Letaba River attributed to excessive allocation and use of water, even without considering further requirements to meet e-flows, the local communities are highly stressed. The synergistic effect of existing low river flows and mandatory e-flows, leading to stress in the communities, is clearly shown by our simulation of the provision of e-flows in the EFLOWS scenario, which considerably increased the crop water gap.

Not surprisingly, when livelihood requirements and e-flows are the focus of water supply in the livelihoods e-flow SUPPL scenario, the crop water gap is eliminated, causing a massive reduction in risk. This improvement in irrigation water availability would certainly have positive implications for the livelihoods of subsistence farmers, who would be able to cultivate crops all year round. The SUPPL scenario, in which sufficient flows for livelihoods as well as e-flows are provided, requires active supplementation of river water to maintain both environmental and livelihoods-oriented river flows. To fully meet the needs of the environment as well as subsistence farmers, considerable volumes of additional water would be needed in most months of most years. It is worth noting that irrigation water demand by subsistence agriculture only amounted to around 2 Mm^3 annually, with median demand never exceeding 300,000 m^3 per month. This is only about one-tenth of the estimated e-flow requirement, a small addition that would make a substantial difference to livelihoods.

The livelihoods e-flow SUPPL scenario has the potential to generate considerable benefits for smallholder farmers, who would see their irrigation water shortages alleviated. Whether or not this scenario is realistic depends on the availability of upstream water resources, as well as the possibility to restrict some of the current uses of water upstream.

Conclusion

The human communities that live close to the Letaba River in the Limpopo catchment depend on the provisioning services derived from the river. These services include fish and other natural products as well as water for subsistence agriculture. This water is a critical requirement for the community to be sustainable. Unfortunately, the water resources of the Great Letaba River are highly utilized, resulting in water stress to the ecosystem, subsistence farmers and commercial users. Today, water resource management policies require that the amount of water needed to sustain ecosystems and the daily domestic water needs of local communities are determined and provided for. These Ecological Reserve flows (e-flows) have been established for the Great Letaba River.

Due to the present pressures on river flows experienced in the Great Letaba River, allocation of water required to meet the e-flows is often considered to be in conflict with development priorities, especially where vulnerable human communities are already stressed. Regulators have generally not communicated the role that e-flows play for sustaining this vulnerable ecosystem and the natural service it provides to local vulnerable human communities.

We acknowledge that for the local communities to be sustainable, domestic water supply and food production are required, and that this food is derived from the river flows used for subsistence agriculture. In this study, we demonstrate that without mitigating the excessive use of water resources by upstream formal commercial agriculture and other users such as urban centers and industries, meeting e-flows from the existing river flows will only exacerbate the stress of reduced flows to the local human communities.

This research identifies the importance of prioritizing subsistence agriculture and the associated water needs of a community for real sustainability, and aligning these requirements with e-flows to achieve a sustainable ecosystem in support of the human communities who depend on these ecosystems. This issue of potential competition between livelihoods and ecosystems is considered to extend across the Limpopo Basin, especially in the more arid regions and where communities are relatively poor. This potential gap in water resource prioritization and allocation for sustainable ecosystems and the vulnerable people who depend on these ecosystems needs to be urgently addressed.

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Annex 1. Model Scripts.

This script was generated using the *rmarkdown* (Allaire et al. 2021) and *knitr* (Xie 2022) packages in the R programming language (R Core Team 2021).

The following script contains the basic model we used to run the Monte Carlo analysis:

```
limpopo_decision_function ← function(x, varnames){

# generating boundary conditions for the simulation run
# simulate how much rainwater is available
  rainfall←sapply(1:12,function(x) eval(parse(text=paste0(“prec_”,x))))

effective_rainfall←sapply(rainfall,function(x) min(x,effprec_high))
effective_rainfall←sapply(effective_rainfall,function(x) max(x,effprec_low))

# We compute crop water need based on ETo based on the Hargreaves Samani Equation, as implemented in the
   Evapotranspiration package. ETo is reference evapotranspiration mm/ha for the model simulations.
# Input temperature data comes from the NASAPOWER dataset (accessed through the nasapower package).
# The scenario data are based on scenarios that represent conditions during real years in the past.
# To get from ETo to crop water use, we need to multiply ETo with a crop coefficient (kc), which is estimated for each
   month.

ETo←sapply(1:12,function(x) eval(parse(text=paste0(“ETo_”,x)))) # in mm

kc←sapply(1:12,function(x) eval(parse(text=paste0(“kc_”,x)))) # in mm

cropwat_need←ETo*kc # in mm

irrigation_need←cropwat_need-effective_rainfall # in mm

# Define river flow and e-flow for each month ####
# Base river flow data from 1920 to 2010 in the Letaba River at EWR site EWR4 (Letaba Ranch upstream of Little Letaba
   confluence).
pre_livestock_river_flow←sapply(1:12,function(x) eval(parse(text=paste0(“river_flow_”,x)))) # in m³/month
e-flow←sapply(1:12,function(x) eval(parse(text=paste0(“e-flow_”,x)))) # in m³/month

# watering livestock
# assuming that this is more or less stable throughout the year, but varies a bit
livestock_water_needs←vv(livestock_water_need,var_CV,12)

# assuming that the e-flows are not affecting ability to water livestock and that there’s always enough water for all
   livestock.
river_flow←pre_livestock_river_flow-livestock_water_needs

# Calculating the farmed area

demand_for_farm_area←n_subsistence_farmers*necessary_farm_size_per_household

farmed_area←min(available_area, demand_for_farm_area)*(1-unused_sociopolit)

total_cropwater_need←cropwat_need*farmed_area*10
```

```
# Total water need in m³ (the 10 is the mm to m³/ha conversion)
total_effective_rainfall←effective_rainfall*farmed_area*10
```

```
# total effective rainfall
# total irrigation need
total_irrigation_need←total_cropwater_need-total_effective_rainfall # in m³
```

```
# water losses are calculated from the efficiency of the pumps and the water allocation
efficiency_pumps←vv(effi_pump,var_CV,12)
efficiency_irrig_scheduling←vv(effi_sched,var_CV,12)
efficiency_pumps←sapply(efficiency_pumps, function(x) min(x,1))
efficiency_pumps←sapply(efficiency_pumps, function(x) max(x,0))
efficiency_irrig_scheduling←sapply(efficiency_irrig_scheduling, function(x) min(x,1))
efficiency_irrig_scheduling←sapply(efficiency_irrig_scheduling, function(x) max(x,0))

water_losses_share←(1-efficiency_pumps*efficiency_irrig_scheduling)

irrigation_water_need←total_irrigation_need/(1-water_losses_share)

# e-flow Scenario 1: No e-flows

scen1_usable_river_flow←sapply(1:12,function(x) max(0,river_flow[x]-minimum_flow_to_operate_pumps))

# e-flow Scenario 2: e-flows as a limit to extraction only

# e-flows are to be ensured whenever there is more water in the river than the e-flow requirement would mandate, i.e.,
  farmers are not allowed to extract water beyond the e-flow requirement.
# no measures are taken to ensure that e-flows are maintained at times when
# the present flow is below the e-flow requirement.

scen2_usable_river_flow←sapply(1:12,function(x) max(0,river_flow[x]-max(e-flow[x],minimum_flow_to_operate_
pumps)))

# e-flow Scenario 3: e-flows are assured by dam releases whenever the present flow is below the e-flow requirement,
water is released from an upstream dam to ensure that the e-flows are met.

adj_river_flow ← sapply(1:12, function(x)
 max(river_flow[x], e-flow[x]))

required_dam_release ← adj_river_flow - river_flow
scen3_usable_river_flow ←
 sapply(1:12, function(x)
  max(0, adj_river_flow[x] - minimum_flow_to_operate_pumps))
```

```
# Calculate how much water gets extracted from the river
```

```
scen1_extracted_river_water ←
 sapply(1:12, function(x)
  min(scen1_usable_river_flow[x], irrigation_water_need[x]))
scen2_extracted_river_water ←
 sapply(1:12, function(x)
  min(scen2_usable_river_flow[x], irrigation_water_need[x]))
scen3_extracted_river_water ←
 sapply(1:12, function(x)
  min(scen3_usable_river_flow[x], irrigation_water_need[x]))
```

```
# Calculate damage to crop production due to lack of irrigation water
```

```
scen1_water_shortfall ←
 sapply(1:12, function (x)
  max(0, irrigation_water_need[x] - scen1_extracted_river_water[x]))
scen2_water_shortfall ←
 sapply(1:12, function (x)
  max(0, irrigation_water_need[x] - scen2_extracted_river_water[x]))
scen3_water_shortfall ←
 sapply(1:12, function (x)
  max(0, irrigation_water_need[x] - scen3_extracted_river_water[x]))
```

```
scen1_irrigation_shortfall←scen1_water_shortfall*(1-water_losses_share)
scen2_irrigation_shortfall←scen2_water_shortfall*(1-water_losses_share)
scen3_irrigation_shortfall←scen3_water_shortfall*(1-water_losses_share)

scen1_crop_water_gap←scen1_irrigation_shortfall/(cropwat_need*farmed_area*10)
scen2_crop_water_gap←scen2_irrigation_shortfall/(cropwat_need*farmed_area*10)
scen3_crop_water_gap←scen3_irrigation_shortfall/(cropwat_need*farmed_area*10)

# Calculate how much water is left after farmers extracted water

scen1_river_flow_downstream←river_flow-scen1_extracted_river_water
scen2_river_flow_downstream←river_flow-scen2_extracted_river_water
scen3_river_flow_downstream←adj_river_flow-scen3_extracted_river_water

# Calculate outputs and differences

return(list(cropwater_need=total_cropwater_need),
        yearly_crop_water_need=sum(total_cropwater_need),
         irrigation_water_need=irrigation_water_need,
         yearly_irrigation_water_need=sum(irrigation_water_need),
         scen1_downstream_river_flow=mean(scen1_river_flow_downstream)
         scen2_downstream_river_flow=mean(scen2_river_flow_downstream),
         scen3_downstream_river_flow=mean(scen3_river_flow_downstream),
         scen3_dam_release=required_dam_release,
         scen3_total_dam_release=sum(required_dam_release),
         Downstream_river_flow_1_=scen1_river_flow_downstream,
         Downstream_difference_2_vs_1=scen2_river_flow_downstream-scen1_river_flow_downstream,
         Downstream_difference_3_vs_1=scen3_river_flow_downstream-scen1_river_flow_downstream,
         scen1_crop_water_gap=mean(scen1_crop_water_gap),
         scen2_crop_water_gap=mean(scen2_crop_water_gap),
         scen3_crop_water_gap=mean(scen3_crop_water_gap),
         Crop_water_gap_scen1_=scen1_crop_water_gap,
         Crop_water_gap_difference_2_vs_1=scen2_crop_water_gap-scen1_crop_water_gap,
         Crop_water_gap_difference_3_vs_1=scen3_crop_water_gap-scen1_crop_water_gap,
         Mean_Crop_water_gap_difference_2_vs_1=mean(scen2_crop_water_gap-scen1_crop_water_gap),
         Mean_Crop_water_gap_difference_3_vs_1=mean(scen3_crop_water_gap-scen1_crop_water_gap)))}
```

Annex 2. Estimate Values for the Monte Carlo Analysis.

This table contains the estimate values used for the Monte Carlo analysis.

Description	Variable	Distribution	Lower	Upper	Label
Precipitation in month 1	prec_1	posnorm	45.00	135.00	Precipitation in January
Precipitation in month 2	prec_2	posnorm	31.00	93.00	Precipitation in February
Precipitation in month 3	prec_3	posnorm	25.00	75.00	Precipitation in March
Precipitation in month 4	prec_4	posnorm	12.50	37.50	Precipitation in April
Precipitation in month 5	prec_5	posnorm	5.00	15.00	Precipitation in May
Precipitation in month 6	prec_6	posnorm	1.00	3.00	Precipitation in June
Precipitation in month 7	prec_7	posnorm	2.00	6.00	Precipitation in July
Precipitation in month 8	prec_8	posnorm	3.00	9.00	Precipitation in August
Precipitation in month 9	prec_9	posnorm	7.00	21.00	Precipitation in September
Precipitation in month 10	prec_10	posnorm	12.50	37.50	Precipitation in October
Precipitation in month 11	prec_11	posnorm	35.00	105.00	Precipitation in November
Precipitation in month 12	prec_12	posnorm	45.00	135.00	Precipitation in December
Reference evapotranspiration (ET_0) mm/per ha month 1 (Hargreaves Samani Equation with nasapower package)	ET_0_1	posnorm	144.00	240.00	Ref. evapotranspiration in January
Reference evapotranspiration (ET_0) mm/per ha month 2	ET_0_2	posnorm	114.75	191.25	Ref. evapotranspiration in February
Reference evapotranspiration (ET_0) mm/per ha month 3	ET_0_3	posnorm	96.00	160.00	Ref. evapotranspiration in March
Reference evapotranspiration (ET_0) mm/per ha month 4	ET_0_4	posnorm	67.50	112.50	Ref. evapotranspiration in April
Reference evapotranspiration (ET_0) mm/per ha month 5	ET_0_5	posnorm	52.50	87.50	Ref. evapotranspiration in May
Reference evapotranspiration (ET_0) mm/per ha month 6	ET_0_6	posnorm	32.25	53.75	Ref. evapotranspiration in June
Reference evapotranspiration (ET_0) mm/per ha month 7	ET_0_7	posnorm	40.50	67.50	Ref. evapotranspiration in July
Reference evapotranspiration (ET_0) mm/per ha month 8	ET_0_8	posnorm	52.50	87.50	Ref. evapotranspiration in August
Reference evapotranspiration (ET_0) mm/per ha month 9	ET_0_9	posnorm	71.25	118.75	Ref. evapotranspiration in September
Reference evapotranspiration (ET_0) mm/per ha month 10	ET_0_10	posnorm	99.75	166.25	Ref. evapotranspiration in October
Reference evapotranspiration (ET_0) mm/per ha month 11	ET_0_11	posnorm	126.00	210.00	Ref. evapotranspiration in November

Continued on next page >>

Description	Variable	Distribution	Lower	Upper	Label
Reference evapotranspiration (ET_0) mm/per ha month 12	ET_0_12	posnorm	145.50	242.50	Ref. evapotranspiration in December
Crop coefficient in month 1	kc_1	posnorm	0.90	1.00	kc_1
Crop coefficient in month 2	kc_2	posnorm	0.90	1.00	kc_2
Crop coefficient in month 3	kc_3	posnorm	0.90	1.00	kc_3
Crop coefficient in month 4	kc_4	posnorm	0.90	1.00	kc_4
Crop coefficient in month 5	kc_5	posnorm	0.90	1.00	kc_5
Crop coefficient in month 6	kc_6	posnorm	0.90	1.00	kc_6
Crop coefficient in month 7	kc_7	posnorm	0.90	1.00	kc_7
Crop coefficient in month 8	kc_8	posnorm	0.90	1.00	kc_8
Crop coefficient in month 9	kc_9	posnorm	0.90	1.00	kc_9
Crop coefficient in month 10	kc_10	posnorm	0.90	1.00	kc_10
Crop coefficient in month 11	kc_11	posnorm	0.90	1.00	kc_11
Crop coefficient in month 12	kc_12	posnorm	0.90	1.00	kc_12
Effective rainfall - minimum threshold	effprec_low	posnorm	5.00	10.00	effprec_low
Effective rainfall - maximum threshold	effprec_high	posnorm	90.00	200.00	effprec_high
		NA NA			
Efficiency of water pumps	effi_pump	tnorm_0_1	0.70	0.90	Efficiency of water pumps
Efficiency of irrigation scheduling and allocation	effi_sched	tnorm_0_1	0.60	0.90	Efficiency of irrigation scheduling
Coefficient of variation, ratio of the standard deviation to the mean (a measure of relative variability)	var_CV	posnorm	5.00	20.00	var_CV
Total irrigable area	available_area	posnorm	100.00	300.00	Available area
Share of land that is not used because of socio-political obstacles	unused_sociopolit	tnorm_0_1	0.20	0.40	Share of unused lands
Number of subsistence households	n_subsistence_farmers	posnorm	30.00	200.00	Number of subsistence farmers
Farm size per subsistence household	necessary_farm_size_per_household	posnorm	1.50	2.50	Needed farm size per household
e-flow in month 1	e-flow_1	posnorm	1,658,637.36	2,487,956.04	e-flow_1
e-flow in month 2	e-flow_2	posnorm	1,953,364.40	2,930,046.59	e-flow_2
e-flow in month 3	e-flow_3	posnorm	2,172,764.83	3,259,147.25	e-flow_3
e-flow in month 4	e-flow_4	posnorm	5,094,152.71	7,641,229.07	e-flow_4
e-flow in month 5	e-flow_5	posnorm	12,093,593.23	18,140,389.85	e-flow_5
e-flow in month 6	e-flow_6	posnorm	4,593,467.28	6,890,200.92	e-flow_6
e-flow in month 7	e-flow_7	posnorm	2,895,912.09	4,343,868.13	e-flow_7
e-flow in month 8	e-flow_8	posnorm	2,484,366.68	3,726,550.02	e-flow_8
e-flow in month 9	e-flow_9	posnorm	2,173,592.97	3,260,389.45	e-flow_9
e-flow in month 10	e-flow_10	posnorm	2,052,485.78	3,078,728.68	e-flow_10
e-flow in month 11	e-flow_11	posnorm	1,670,297.91	2,505,446.86	e-flow_11
e-flow in month 12	e-flow_12	posnorm	1,419,171.87	2,128,757.80	e-flow_12
Minimum river flow that allows running the pumps (in m^3/month)	minimum_flow_to_operate_pumps	posnorm	50,000.00	150,000.00	Minimum flow required by pumps

Continued on next page >>

Description	Variable	Distribution	Lower	Upper	Label
river flow in month 1 (Taken from base flow (Mm^3/a) data from 1920 to 2010 (Letaba River at EWR site EWR4 (Letaba Ranch upstream Little Letaba confluence)))	river_flow_1	posnorm	3,289,641.29	14,884,566.58	River flow in January
river flow in month 2	river_flow_2	posnorm	35,521,90.55	28,211,390.25	River flow in February
river flow in month 3	river_flow_3	posnorm	3,629,341.05	24,557,111.18	River flow in March
river flow in month 4	river_flow_4	posnorm	3,593,958.87	18,063,311.23	River flow in April
river flow in month 5	river_flow_5	posnorm	3,506,617.70	11,756,278.83	River flow in May
river flow in month 6	river_flow_6	posnorm	3,448,532.21	8,821,373.46	River flow in June
river flow in month 7	river_flow_7	posnorm	3,270,609.32	7,597,819.59	River flow in July
river flow in month 8	river_flow_8	posnorm	2,770,310.63	6,595,355.44	River flow in August
river flow in month 9	river_flow_9	posnorm	2,475,234.52	5,976,080.25	River flow in September
river flow in month 10	river_flow_10	posnorm	2,195,340.50	5,425,988.65	River flow in October
river flow in month 11	river_flow_11	posnorm	2,306,113.10	6,163,707.61	River flow in November
river flow in month 12	river_flow_12	posnorm	2,699,506.90	7,293,206.41	River flow in December
livestock water need per month	livestock_ water_need	posnorm	300.00	2,000.00	livestock_ water_need

Annex 3. Glossary.

Environmental flow: Water in a river or wetland that maintains the ecosystem and the benefits it provides to people.

Aquatic agricultural systems: Agricultural systems in which the annual production dynamics of freshwater and/or saline or brackish coastal systems contribute significantly to total household income.

Stressors: Factors affecting an ecosystem negatively.

Partial Least Squares: An estimation technique that reduces the predictors to a smaller set of uncorrelated components and performs least squares.

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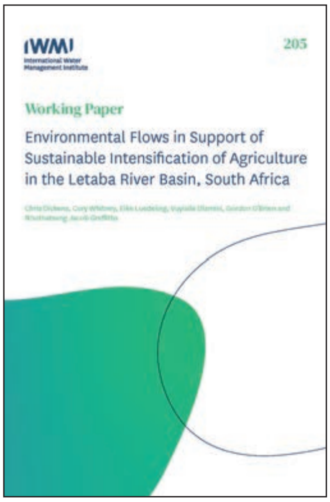

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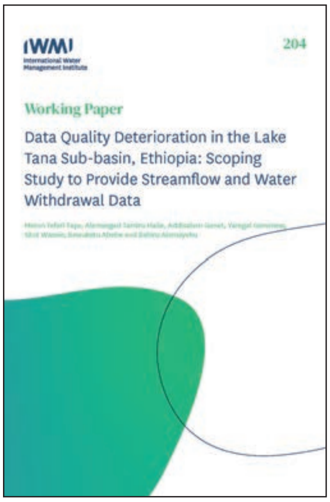

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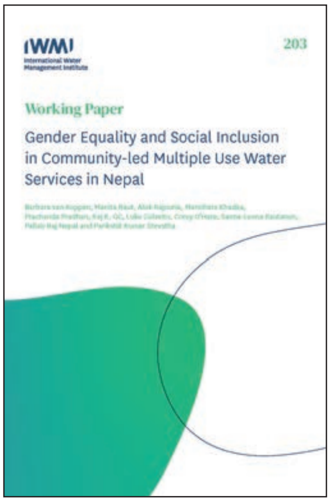

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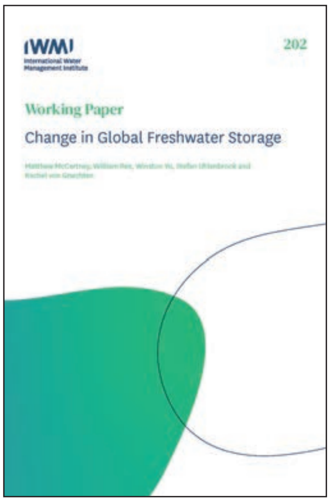

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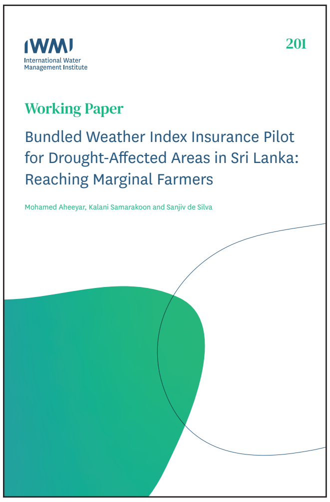

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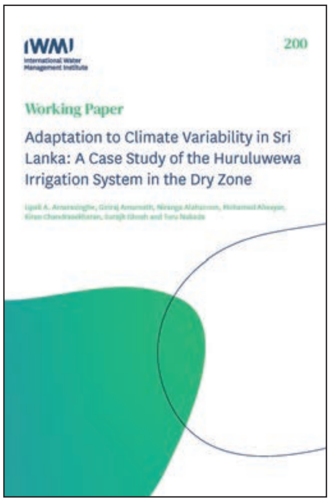

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Headquarters
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Mailing address
P. O. Box 2075
Colombo
Sri Lanka

Telephone
+94 11 2880000

Fax
+94 11 2786854

Email
iwmi@cgiar.org

Website
www.iwmi.org

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ISSN 2012-5763
e-ISSN 2478-1134
ISBN 978-92-9090-947-7