ECONOMIC VIABILITY OF RAINWATER HARVESTING AND IRRIGATION DEVELOPMENT INTERVENTIONS IN ETHIOPIA AND KENYA: AN APPLICATION OF STOCHASTIC IMPACT EVALUATION

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A80/50382/2016

A THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN AGRICULTURAL AND APPLIED ECONOMICS

DEPARTMENT OF AGRICULTURAL ECONOMICS
FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

JULY 2023

Declaration

I declare that this thesis is my original work and has not been submitted elsewhere for examination or award of a degree.

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Dedication

To my parents

To my wife, Ngsti and My children, Natanim, Ezana, Saizana, and N'eud

God bless you!

Acknowledgements

My sincere gratitude goes to the almighty God for granting me a healthy and peaceful life as well as the infinite support to successfully complete this PhD study.

This doctoral study would not have been possible without the support from many individuals and institutions. I am deeply grateful to my supervisors, Prof. John Mburu, Prof. Chris Ackello-Ogutu, and Prof. Eike Luedeling, for providing continued guidance, support, and encouragement. You have taught me as well as allowed me to learn in my own way. I wish to express my gratitude to Dr. Cory Whitney, Dr. Tesfamichaele Wossen, and Dr. Mulugeta Mokuria as well. They are indeed a friendly professional who provided me with fabulous ideas which truly were prolific for the successful accomplishments of my academic endeavor.

I also wish to express my sincere appreciation to the German Academic Exchange Program (DAAD) and World Agroforestry Centre (ICRAF) for funding the PhD studies through the "In Country/In Region" scholarship program. I also acknowledge Mrs. Imeleda Ingumba and Mr. Samuel Gaturu for their support during the doctoral studies. I also would like to thank the DAAD and ICRAF program leaders and coordinators who directly and/or indirectly supported the research works. Furthermore, my heartfelt thanks also go to experts who actively participated during the different workshops and devoted their time as well as provided me with relevant data to prepare the papers.

Last, but not least, I would like to thank my wife, Ngsti Gebreegziher, and my children, Natanim, Ezana, Saizana and N'eud, for their great support, love and sacrifice during this journey. I am also thankful for Dr. Ermias Betemariam and Dr. Lisa Fuchs for their valuable comments and suggestions during my research work.

Abstract

Alleviating poverty and meeting the growing demand for food is the top priority for economic and social development of the developing world. Accordingly, countries have been investing substantial amounts of their budget to develop agricultural infrastructure, such as rainwater harvesting and irrigation development structures. Considering the dependency of the communities in rainfed farming systems, the demand for rainwater harvesting and irrigation development is expected to increase. However, development planners and/or decision makers are facing difficulty in prioritizing alternative investments. Because such investments are complex and full of uncertainties. In this regard, Stochastic Impact Evaluation (SIE) technique is applicable to reduce prediction uncertainties and produce reliable information that can help decision and policy makers in prioritizing intervention options under system complexity and data scarcity.

Despite the wide applicability of SIE, the technique is rarely, as well as recently, applied to evaluate agricultural development interventions. It is not yet applied to evaluate rainwater harvesting and irrigation development interventions. In addition, there is no existing literature on the viable rainwater harvesting and irrigation development interventions that captures the system complexity and prediction uncertainty. Therefore, the objective of the study is to assess the economic viability of rainwater harvesting and irrigation development interventions using SIE by taking an irrigation dam construction, road-water harvesting, and spate irrigation system interventions as a case study in Ethiopia and Kenya respectively.

In the first objective, the economic viability of an irrigation dam development project in northern Ethiopia was evaluated. Model results indicate that the proposed irrigation dam project is highly likely to increase the overall benefits and improve food and nutrition status of local farmers. However, the overall value of these benefits is unlikely to exceed the sum of the investment costs and negative externalities involved in the intervention. Moreover, the simulation results suggest that the planned irrigation dam may improve income, as well as food and nutrition security, but would generate negative environmental effects and high investment costs.

In the second objective, the economic viability of road-water harvesting structures was assessed for Tigray region of Ethiopia. We find that the proposed road-water harvesting structure is likely to produce net benefits and improve the income of the households who live in the vicinity of the roads. However, the magnitude of the net benefits varies with type of road-water harvesting structures. The overall simulation results indicate that harvesting road-water using percolation structures is viable, whereas this does not seem to be the case for check dams. The result also identified construction cost of the structure, water holding capacity of the structure, water use efficiency and farm revenue as the most sensitive parameters that influence the simulated outcome. Furthermore, our result also indicated that the outcome for harvesting water with either farm ponds or a combination of all structures is uncertain and further measurement is required.

In the third objective, the communal and environmental costs, benefits and risks of introducing a spate irrigation system in Turkana County were identified. Furthermore, the economic viability of developing spate irrigation systems in Turkana County, Kenya were assessed. The model result indicates that spate irrigation developments are likely to benefit the local communities as well as the environment. The return to investment is negatively correlated with the size of the structure. Furthermore, the chance of generating negative Net Present Value (NPV) increases with the size of the structure. The result also indicated that the communities in Turkana county could improve their household income if the government and/or non-governmental development agents invest in the development of viable spate irrigation infrastructures.

Rainwater harvesting and irrigation development structures have the potential to improve agricultural production, household income, and at the same time create climate change resilient communities that withstands drought, dry spells, and flooding. However, this could lead us to incur higher investment cost, especially when the structure is big, such as an irrigation dam, which in return lowers its viability. The study revealed the applicability of SIE technique to evaluate agricultural development interventions in the face of system complexity, predictive uncertainty and data scarcity.

Key words: Water harvesting, Feasibility assessment, Uncertainty, Ex-ante appraisal, Food security, Decision support, Agricultural development intervention, East Africa

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List of abbreviations

AGRA	Alliance for Green Revolution in Africa
BCR	Benefit-Cost Ratio
ETB	Ethiopian Birr
EVPI	Expected Value of Perfect Information
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
Ha	Hectare
IFAD	International Fund in Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
KNBS	Kenya National Bureau of Statistics
KSh	Kenyan Shilling
MCS	Monte Carlo Simulation
NBE	National Bank of Ethiopia
NPV	Net Present Value
PLS	Partial Least Square
SI	Spate Irrigation
SIE	Stochastic Impact Evaluation
SSA	Sub Saharan Africa
UN	United Nations
US	United States
UNICEF	United Nations International Children's Emergency Fund
VIP	Variable of Importance in Projection
VoI	Value of Information
WFP	World Food Program
Yr	Year
$	United States Dollar

CHAPTER ONE: INTRODUCTION

1.1. Background

Food insecurity and poverty are the most alarming challenges in the developing world. The status of food and nutritional security report (FAO, IFAD, UNICEF, WFP, 2018) has shown that a considerable number (i.e. about 821 million) of the global population is living under chronic food deprivation, indicating the immense challenge of achieving zero hunger by 2030. The efforts under the Millennium Development Goal initiative significantly reduced the number of chronically food deprived people (UN, 2015). Despite the unprecedented reduction in the level of poverty and food insecurity over the last couple of decades, the trend in Sub Saharan Africa's (SSA) has changed since 2015 (FAO, IFAD, UNICEF, WFP, 2018). The total number of undernourished people in SSA increased from 202 million in 2015 to 239 million in 2018 (ibid). Furthermore, the report showed that more than half of the SSA population (i.e. about 605.8 million) is experiencing moderate to severe food insecurity (ibid). Considering the reliance of the majority of SSAs' population in agriculture, the food insecurity situation in the region is expected to increase. Because most of the farmers are dependent on a rain fed system, which is subject to the precarious nature of the climate extremes (AGRA, 2014).

Alleviating poverty and meeting the growing demand for food that emanates from population growth is the top priority for economic and social development of the developing world. The global population is projected to exceed nine billion by 2050, of which the majority of them are in less developing countries. In order to meet the growing food demand, the current agricultural production capacity should be increased by 50% (Jury and Vaux, 2007). Accordingly, countries must invest a substantial amount of their budget to develop agricultural infrastructures, such as rainwater harvesting and irrigation development structures. Recently, SSA countries showed promising changes in the budget allocated to agricultural production. These countries are compelled to increase their agricultural expenditure from 6% to 10% of their budget (AGRA, 2019). However, very few countries achieved this target. For example, the budget on agricultural expenditure in Ethiopia reached 10% in 2005, which is the target set during the Maputo declaration' (Karugia et al., 2014).

In SSA countries in general, and Ethiopia and Kenya in particular, agriculture contributes more than one-third to the gross domestic product (GDP) and employs more than three-fourth of the population. Despite its importance, agricultural production and productivity is extremely low. This might be linked to smaller farm size, low financial capability of farmers to buy agricultural input, farmer's technical inefficiency and limited commercial market participation (AGRA, 2014). Generally, subsistence agriculture heavily depends on available rainfall, implying that climate variability and change possibly affects the sector severely and will exacerbate the vulnerability of poor farmers to different climate-change induced shocks. Moreover, climate change represents a major threat for the coming decades, particularly in Africa (IPCC, 2007; AGRA, 2014) which has more climate sensitive economies than any other continent.

Agriculture production and productivity have a vast potential for improvement in both Kenya and Ethiopia (AGRA, 2014). However, the traditional rain-fed dependent and subsistence farming system might need to undergo a transformation towards a more modern and resource efficient production system. For example, climate change in eastern Africa and Ethiopian highlands will increase surface runoff (AGRA, 2014). Thus, efficient utilization of runoff water will lead to higher agricultural production and improve the livelihood of the community, while mismanagement and lack of adequate infrastructure can increase occurrence of floods and potentially damage the societal wellbeing.

Therefore, it is timely and crucial to improve utilization of available water resources (i.e. floods) (Puertas et al., 2015) to supplement rain fed agricultural systems and boost productivity and societal wellbeing across the region (Sander et al., 2011; Erkossa et al., 2014; Hiben et al., 2014). Improved rainwater utilization requires water harvesting structures either in the farm or/and out of the farming plots (AGRA, 2014; Erkossa et al., 2014). Accordingly, coordinated agricultural investment is required to reduce poverty and hunger through efficient water utilization and simultaneously promoting environmental sustainability (FAO, 2013a; AGRA, 2014). Thus, governments and development agents should direct their investment in public goods, such as rural infrastructure, research and development, as well as education, rather than investing in private goods, such as input subsidies; because investing in the former is instrumental to reduce poverty and improve food and nutrition security (FAO, 2013a).

In SSA, climate and non-climate factors could potentially affect land productivity and agricultural production. Consequently, soil moisture stress is one of the most prevalent factors that lead to reduction in agricultural production as well as increase the level of food insecurity and poverty (Hatibu et al., 2006; Namara et al., 2010). Rainwater harvesting is therefore a promising practice that addresses the rainfall variability and thereby increases agricultural production and productivity in a rain-fed system (Girma et al., 2018). Rainwater harvesting enhances efficient resource utilization and promotes sustainable agricultural production during the events of seasonal dry spells and droughts. Thereby it helps to develop the adaptive capacity of the rural poor.

The importance of rainwater harvesting and irrigation development is well studied (e.g. Hanjra et al., 2009; de Fraiture et al., 2010; Rockström et al., 2010; Moges et al., 2011; Biazin et al., 2012; Hagos et al., 2013;). Gebregziabher et al. (2009) reported that farmers with access to irrigation gains more income than those without access. Another study by Hagos et al. (2012), revealed that the incidence of poverty among different irrigating farmers in four regions of Ethiopia was reduced by using micro-dams, ponds, deep-walls and river diversion structures. Access to consistent water sources improves agricultural production and productivity, increases employment opportunities, and enhances income and consumption (Namara et al., 2010). In general, countries that utilized yield enhancing technologies, such as irrigation, have been achieving higher levels of agricultural productivity (Karugia et al., 2014). Furthermore, farmers with access to water harvesting structures have a higher share of market participation and asset endowments (Hagos et al., 2013).

However, it is evident that the impact of water harvesting structure on poverty and food insecurity is directly related to the technology used, crop type, agro ecology, and regions (Molden et al., 2010; Hagos et al., 2012, 2013). The value of water harvesting structure is significant in areas with high levels of poverty, physical water scarcity, and low water productivity (Molden et al., 2010). For better poverty reduction impacts, water harvesting and agricultural water management strategies should empower the rural poor to have access to reliable water sources through securing water rights and investing in water harvesting structures (Namara et al., 2010). Moreover, although irrigation investments reduce the incidence of poverty and improve the living standard of many poor farmers, some have been unsuccessful and generate notably external costs (de Fraiture et al., 2010). With poor water management, irrigation infrastructures increase the incidence of malaria and other waterborne diseases and deteriorate the health of the people who live close to the structures (Lire, 2005). Furthermore, the construction of water harvesting infrastructures could displace farmers from their homes and lead to higher socio-cultural costs (Tilt and Gerkey, 2016).

In SSA, the majority of the farmers are poor and reliant on rain fed farming systems (AGRA, 2014). The precarious nature of the weather and the negative impacts of climatic extremes are expected to further jeopardize the living standard of the rural community and increase the number of people living under extreme poverty (Calzadilla et al., 2013). This situation is a clear threat to the efforts that have been implemented to end hunger and food insecurity. Accordingly, there is a growing demand for rainwater harvesting and irrigation development interventions to develop adaptive capacity of the poor farmers and enhance agricultural productivity. However, detailed evaluation of the interventions is therefore mandatory to optimize the returns from the investment.

1.2. Statement of the problem

Agricultural development interventions, policies, and programs are complex, where anticipating future impacts are difficult. Most of the methodologies used to evaluate agricultural development projects do not capture the inherent uncertainty, especially when the system is complex (Luedeling et al., 2015; Luedeling and Shepherd, 2016; Lanzanova et al., 2019). Furthermore, the outcome of agricultural development interventions, such as installation of rainwater harvesting structures, are influenced by environmental, social and economic factors (Molden et al., 2010; Hagos et al., 2013; Luedeling and Shepherd, 2016). Yet, current approaches and methods used in the planning and implementation of agricultural development projects and programs do not capture all the plausible streams of costs, benefits and associated risks (Luedeling et al., 2015). For example, in the typical investment appraisal methods, such as cost-benefit analysis (CBA), environmental, social and political costs and benefits are often neglected. In addition, according to Kalra et al. (2014), the streams of costs and benefits in traditional cost-benefit analysis are often computed based on an agreed risk neutral environment. However, in reality, the degree of risk-taking behavior varies across different actors (i.e. some of the actors are risk-averse in nature while others are risk takers).

Investments in agricultural development and policy decisions have long term consequences. Impacts that are difficult to predict, especially where information and data are limited, leave decision-makers with little support for the decisions they face. Developing countries, especially in Sub-Saharan Africa, have a big gap in data availability because data are either unavailable or costly to collect (Shepherd et al., 2015). Lack of appropriate tool to address the above-mentioned challenges constrains decision makers and development planners from making informative decision (Peterman and Anderson, 1999; Luedeling et al., 2015). Failure to consider various risks might lead to poor decisions, which may have detrimental impacts on stakeholders (Peterman & Anderson, 1999; Hubbard, 2014; Kalra et al., 2014; Luedeling et al., 2015; Shepherd et al., 2015).

Decision-focused agricultural research overcomes the challenges that decision makers often face by capturing most, if not all, dimensions of the proposed intervention (Luedeling et al., 2015). In contrast to the usual research that intends to generate knowledge, decision focused research is helpful in solving complex decisions (Luedeling and Shepherd, 2016). This is also called Stochastic Impact Evaluation (SIE) technique (Wafula et al., 2018). (SIE) integrates all plausible monetary and non-monetary streams of costs, benefits, and risks in the impact pathway model. More importantly, it captures the uncertainty in future streams of costs and benefits as well as future risks of the interventions. It also addresses data gaps that often prevent decision makers from making the best-informed choices. Thus, the technique is instrumental in supporting the formal decision-making process under system complexity, uncertainty, and data scarcity (Luedeling et al., 2015; Whitney et al., 2017; Lanzanova et al., 2019;). Moreover, SIE is also applicable in identifying the uncertain variables that have a great impact on the decision outcomes and help decision makers to prioritize further measurements only on those variables that might change their decision (Luedeling et al., 2015; Wafula et al., 2018). This avoids spending resources on measuring variables that have no or little effect on the decision (Shepherd et al., 2015; Luedeling and Shepherd, 2016).

In other disciplines, the application of Stochastic Impact Evaluation (SIE) is widely recognized (Hubbard, 2014). However, its application to agricultural science is very new. The World Agroforestry Centre (ICRAF) has been taking the initiative to adopt the methodology to different agricultural and water supply settings. So far, a study on the viability of water supply project in Wajir, Kenya (Luedeling et al., 2015), honey value chains in Lamu, Kenya (Wafula et al., 2018), reservoir protection in Burkina Faso (Lanzanova et al., 2019), and forest landscape restoration (Tamba et al., 2021) have been conducted. Moreover, the approach was also used to assess the nutritional and food security outcome of home-garden in Uganda (Whitney et al., 2017). Furthermore, the relevance of the approach to agriculture research (Luedeling and Shepherd, 2016) as well as towards the cost effective monitoring Sustainable Development Goals (Shepherd et al., 2015) were presented. However, despite the potential usefulness and applicability of SIE, its application to rainwater harvesting and irrigation development interventions were lacking.

1.3. Objectives

1.3.1. General objective

The main objective of this study was to assess the economic viability of rainwater harvesting and irrigation development interventions using Stochastic Impact Evaluation technique by taking an irrigation dam construction, road-water harvesting, and spate irrigation systems intervention as case studies in Ethiopia and Kenya, respectively.

1.3.2. Specific objectives

In line with the above-mentioned general objective, the study was guided by the following specific objectives. To:

1. Assess the economic viability of a dam construction project in Tigray Regional State, Ethiopia,
2. Evaluate the economic feasibility of road-water harvesting interventions in Tigray Regional state, Ethiopia

3. Identify the communal and environmental costs, benefits, and risks of introducing spate irrigation intervention in Turkana county, Kenya

1.4. Research questions

The study answered the following research questions.

1. What is the economic viability of investing in an irrigation development intervention in Tigray Regional state, Ethiopia?
2. How economically feasible is it to have road-water harvesting interventions in Tigray Regional state, Ethiopia?
3. What are the environmental and communal costs, benefits and risks of introducing spate irrigation intervention in Turkana County of Kenya?

1.5. Justification

Agricultural development decisions are constrained due to system complexity, inherent uncertainty and data scarcity. The lack of appropriate tools for *ex-ante* evaluation is one of the main constraining factors in development decisions. In such a context, decisions are made based on perceived technical feasibility. However, failure to capture the risk and uncertainties could lead to suboptimal decision outcomes. To address such challenges, scholars in the field of decision science have been engaged in developing tools. Researchers in agricultural science are considered Stochastic Impact Evaluation (SIE) as one of the innovative techniques to address such challenges. Despite the wide applicability in other disciplines, SIE is a newly adopted technique in agricultural science. Therefore, the result of this study will contribute towards filling the methodological gap in the literature. Moreover, the results of this study will also benefit different stakeholders and decision makers by providing them with an approach that improves decision-making by capturing the uncertainty of future costs and benefits and the associated risks of their interventions.

Unlike the other *ex-post* studies, this was assessed the economic viability of rainwater harvesting and irrigation development interventions by taking an irrigation dam, road-water harvesting, and spate irrigation interventions in Ethiopia and Kenya, respectively. The study was considered the case studies as a separate system and captures most, if not all, monetary and non-monetary benefits, costs and risks. The study therefore contributes towards filling the empirical literature gap on viability of rainwater harvesting and irrigation development interventions in SSA in general, and Ethiopia and Kenya in particular.

1.6. Scope and limitations

The demand for rainwater harvesting and irrigation development is growing throughout the developing world. *Ex-ante* evaluation of proposed interventions is therefore necessary for optimal allocation of funds. Although it is evident that covering more study areas could improve the understanding of rainwater harvesting and irrigation development intervention, due to time and resource limitation I opted to cover only the Tigray region of Ethiopia and Turkana county of Kenya. Furthermore, these studies were carried out by collecting data from experts who have more knowledge about the subject matter under study. Accordingly, the opinion of the main stakeholders (i.e. farmers and water use associations) were not addressed in this studies.

1.7. Organization of the thesis

This thesis is organized in seven chapters:

Chapter one: The first chapter is a general introduction into the subject under study. It covers a background on the need for rainwater harvesting and irrigation development structure, statement of the problem, objectives of the study, and scope and limitations of the study.

Chapter two: The second chapter is a summary of the existing literature. It covers the theoretical background and past theoretical studies about an irrigation dam construction, spate irrigation and road-water harvesting.

Chapter three describes the methodological part of the study. Though all the chapters have their own methodological description, this chapter uses the methodology used for the first objective of the thesis as a case study, which is published in the Data in Brief journal[1].

[1] Yigzaw, N., Mburu, J., Ogutu, C.A., Whitney, C., Luedeling, E., 2019b. Data for the evaluation of irrigation development interventions in Northern Ethiopia. Data Br. 25. https://doi.org/10.1016/j.dib.2019.104342

The research questions are addressed in chapters four to six. The fourth chapter is presenting the result of the first objective. In this chapter the economic viability of an irrigation dam construction intervention in Tigray region of Ethiopia was assessed. The dam construction intervention was evaluated with and without restoration of the catchment area. In this study, the most sensitive variables that influence the dam construction outcome were identified. The parameters with a critical knowledge gap; and that needs further measurement were also identified using the Value of Information analysis. This paper is published in *Science of The Total Environment*[2] journal.

Chapter five is about the economic feasibility of road-water harvesting interventions in Northern Ethiopia. This section addressed the second objective of the study. The economic feasibility of harvesting road-water using percolation ponds, farm ponds, check dams as well as a combination of all the three different structures were evaluated and discussed. The most uncertain parameters that strongly influence the road-water harvesting outcome were identified. Furthermore, the critical knowledge gaps that need further measurement were also identified.

Chapter six presents the results based on objective three. It identifies the communal and environmental costs, benefits, and risks of introducing spate irrigation systems in Turkana County, Kenya. It also assesses the economic viability of introducing a spate irrigation system. The economic viability of introducing two spate irrigation systems was evaluated (i.e. based on the size of the area that can be irrigated). The most sensitive parameters that influence the intervention outcome were identified. The critical knowledge gaps that need further measurement were also identified.

Chapter seven provides a general conclusion of the study and forward recommendation for future action. Limitation of the study and area for further research are also highlighted in this section.

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2 Yigzaw, N., Mburu, J., Ackello-Ogutu, C., Whitney, C., Luedeling, E., 2019a. Stochastic impact evaluation of an irrigation development intervention in Northern Ethiopia. Sci. Total Environ. 685, 1209–1220. *https://doi.org/10.1016/j.scitotenv.2019.06.133*

CHAPTER TWO: LITERATURE REVIEW

2.1. Agricultural water management and poverty reduction strategies

Water scarcity is the critical challenge for the majority of the people who reside in the global south, specifically, for the rural poor that are entirely reliant on rain fed systems. Based on the assessment of fresh water scarcity, about four billion people in the globe are experiencing water scarcity for at least one month in a year (Mekonnen and Hoekstra, 2016). A comprehensive study on the management of agricultural water indicated a clear need for investment in managing rainwaters and optimizing returns from it (Hanjra et al., 2009a; de Fraiture et al., 2010). Because agriculture uses the majority of the water sources; and improvement in efficiency of agricultural water leaves room for utilizing it optimally, maintaining the environment, and enhancing social as well as economic development. Thus, in a place with exploitable water source and difficulties of accessing them by the communities, interventions in new agricultural water infrastructures, such as small scale irrigation, spate systems, and large scale irrigations seems promising (Namara et al., 2010; Hagos et al., 2014).

Water management and poverty are highly interlinked (Namara et al., 2010). The incidence of food insecurity is higher in areas with low investment in water harvesting technologies, such as Sub Saharan Africa. For example, close to a billion people in the world, which are rural poor that are engaged primarily in agriculture under a rain fed system, are living under chronic food deprivation (FAO, IFAD, UNICEF, WFP, WHO, 2019). The linkage between poverty and agricultural water management was studied by Namara et al., (2010). According to the authors, improving the management of agricultural water reduces the level of poverty through three pathways. *First*, access to reliable water sources improves agricultural production and productivity, increases employment opportunities, and stabilizes household income and consumption. *Second*, the utilization of agricultural yield enhancing technologies or inputs are encouraged and promote diversification of products, which in return creates an opportunity for non-farm output and employment, and meets multiple needs of the households. *Third*, it improves the nutrition, health and social status of the people.

Population is growing at an alarming pace and by the mid-21st century, the global population will have increased by about three billion. To feed the growing population, food production should be increased by about 50%, assuming constant farm productivity (Jury and Vaux, 2007). It is evident that there is enough water and land to feed the growing population (de Fraiture and Wichelns, 2010), yet little has been done in agricultural water management. Thus, agricultural intensification and proper water harvesting has a paramount importance in providing enough food to the growing population as well as reducing food deprivation (Dile et al., 2013). If there is no action on the '*water for food security*' situation, it might be intricate or get daunting.

The agricultural water management practices should be prioritized based on the area that shows promising increase in water productivity (Molden et al., 2010). According to the authors, the priority areas for increasing water productivity are categorized into four. The *first* intervention is to prioritize areas with low water productivity and high levels of poverty. The *second* is in areas with high water scarcity and highest competition for water. The *third* is in areas with limited water resource development, but has higher return from each extracted water. The *fourth* is in areas with high ecosystem degradations resulting from water. The impact on poverty reduction is higher when there is well developed human capital and rural markets (Hanjra et al., 2009a). Thus, agricultural water management interventions should not be implemented separately, rather it should be complemented with other social, human, and economic policies (Hanjra et al., 2009a; Namara et al., 2010).

Irrigation can and will continue playing a significant role in feeding the growing population as well as reducing the existing poverty and food insecurity (Turral et al., 2010). However, investing only in irrigation is not enough. Therefore, efforts as well as investments should be made to increase agricultural productivity in a rain-fed system, promoting agricultural trade, and limiting the potential increment in food demand (de Fraiture and Wichelns, 2010). Furthermore, poverty reduction strategies should: (1) ensure the water rights for the poor and investments in water harvesting infrastructures; (2) empower people for efficient utilization; (3) improve water governance; and (4) support farmers to diversify their livelihood options (Namara et al., 2010).

2.2. Investment in rainwater harvesting and irrigation development

Rainwater harvesting and irrigation development interventions are crucial in reducing poverty and food insecurity (Hagos et al., 2013; Bouma et al., 2016; Girma et al., 2018). Rainwater harvesting interventions show a significant increase in crop yield (Bouma et al., 2016), while the magnitude varies with the type of water harvesting structures (Hagos et al., 2013). Another study by Senkondo et al., (2004), found that rainwater harvesting interventions improves factor productivity. In areas with low and predicted further decline in rainfall (i.e. arid and semi-arid areas), the construction of rainwater harvesting structures, such as farm ponds, earth as well as subsurface dams, and tanks, is gaining attention (Ngigi, 2009).

Though many water harvesting structures and irrigation investments increase agricultural productivity and improve livelihoods, some poorly conceived or implemented interventions are generating negative externalities (Amdihun, 2008; Kibret et al., 2008; de Fraiture et al., 2010). Furthermore, harvesting all the available rainwater for irrigation purposes, however, is neither possible nor recommended. According to de Fraiture et al., (2010), investment in water harvesting interventions are expected to face the following tradeoffs: (1) allocating water for agricultural purpose and the environment; (2) allocating water between upstream and downstream area; (3) reallocation of the water and over allocation; (4) equity and productivity; and (5) utilizing the water for the current generation and future generation. Yet, optimum utilization of the rainwater could reduce the tradeoffs and improve overall benefits. The tradeoffs between the different users of the rainwater, such as the environment and agriculture, should be considered during the planning phase (de Fraiture et al., 2010).

2.3. Theoretical background of investment in rainwater harvesting and irrigation development

2.3.1. Investment decisions in rainwater harvesting and irrigation development

Human beings always face alternatives that need decisions in almost all their daily activities. They decide, for example, on what and when to eat, when to walk up and go to bed, what to do etc. These decisions are made based on the perceived relevance and utility of the decision maker (i.e. rational decision Making). According to the principles of 'rational decision making', a rational decision maker analyzes the alternatives from different perspectives and selects the one that has the highest expected utility (Mankiw, 2006). Expected utility is defined as "a weighted average of the values of the outcomes, discounting each by the probability of being true if the action is performed" (Pollock, 2004). It is described as the sum of all the utilities obtained from the possible outcomes multiplied by the probability of occurrence. Thus, to make a decision, there should be at least two alternatives with different payoffs (Hubbard, 2014) and there should be a negative or lower outcome for selecting the wrong alternative (Oliveira, 2007).

Economic theory suggest that decision makers are making investment decisions based on the expected change in the level of utility, where technically 'utility' in investment decisions is related to the return from the investment, which can be measured in monetary or non-monetary term (cf. Lire, 2005; Hagos et al., 2013). For rainwater harvesting and irrigation development interventions, a decision or policy maker approves the construction of the structures if the expected return from the investment is higher than the current value of the investment.

2.3.2. Risk and uncertainty in rainwater harvesting and irrigation development

Predicting the outcome of rainwater harvesting and irrigation development intervention is difficult. It is full of risk and uncertainties. Scholars have been developing tools to integrate the risks and uncertainties during the project appraisal and planning phase. The better option, so far, is to simulate the outcome of the proposed intervention based on available knowledge and show the whole spectrum. Accordingly, decision or policy makers try to deal with this uncertainty by assigning probabilities to those outcomes. In a situation of uncertainty, decision makers should choose the investment alternative with the highest expected value. The expected utility theorem provided by von Neumann and Morgenstern (1944), suggests that for a rational decision making, a rational agent with two alternatives (i.e. A_1 and A_2) prefers A_1 if the expected utility from A_1 is greater than A_2. In general, a rational decision maker maximizes the return from each investment by selecting the alternative with higher expected return.

Decision-making processes related to investments in agricultural development, such as installation of rainwater harvesting and irrigation development structures are difficult. Rainwater harvesting and irrigation development structures are complex systems, which are subject to a lot of risk and uncertainties. Because, investment in irrigation and water harvesting structures are subject to different stochastic parameters. In principle, the impacts of any investment decisions or policy changes that have long-term consequences are difficult to predict accurately (Kalra et al., 2014). For example, decisions on large-scale rural infrastructure, such as roads or irrigation schemes, or on agroforestry interventions, require a clear understanding of the system. Failure to account for all the associated uncertainties may lead to suboptimal decision outcomes (Luedeling et al., 2015).

2.4. Empirical studies on rainwater harvesting and irrigation development interventions

Water harvesting and retention systems are of particular importance in arid and semi-arid areas, such as Ethiopia and Kenya, where rain-fed agricultural production faces severe drought and dry spell risks (Roden et al., 2016; Girma et al., 2018). Rainwater harvesting interventions are recommended in areas with annual rainfall of 300 -1200 mm (Ngigi, 2009). In these areas, investment in water harvesting and irrigation development interventions significantly increases agricultural yield, income and employment opportunities (Amede et al., 2008; Awulachew and Yilma, 2008). Given a large proportion of sub-Saharan African population living in arid and semi-arid rural areas, investment in water-related infrastructures could benefit 58% of the rural population (Faurès and Santini, 2008).

African countries have enough potential to expand their irrigable area. The total irrigable area equipped for irrigation in Africa was slightly more than 15 million, which is close to seven percent of the total arable land of the continent, and this is much less than the global average of 23.4% (FAOSTAT, 2014). There is a possibility of expanding dam based irrigated land by 16.3 million hectares, of which 8.4 million hectares is from existing dams, one million hectares from rehabilitated structures, and the remaining by constructing new reservoirs. Another study by You et al. (2011), estimated the potential of dam based and small scale irrigation potential at 24 million hectares. Thus, the expansion potential of irrigable areas is higher in SSA (You et al., 2011; Xie et al., 2014).

2.4.1. Irrigation development intervention

Investment in irrigation development infrastructures help countries to reduce poverty, improve food and nutrition security, and adapt to the impacts of climate change (cf. Berhane et al., 2016; Hagos et al., 2017). The impacts of investment in rainwater harvesting and irrigation development interventions are well documented (e.g. Gebregziabher et al., 2009; Hagos et al., 2009; Hanjra et al., 2009a, 2009b). A study by Hagos et al. (2012) indicated that the incidence of poverty in Ethiopia is reduced by 37, 26, 11, and 9% when households use micro dams, deep wells, diversions and ponds respectively. Another study on the expansion of smallholder irrigation in Sub-Saharan Africa shows that investment in water harvesting strategies (i.e. motor pump, treadle pump, small reservoir, and communal diversions) could benefit 113 to 369 Million rural people with annual revenue of between 14 to 22 billion US dollars (Xie et al., 2014).

Furthermore, accessing irrigation schemes improves agricultural yield as well as household income (Gebregziabher et al., 2009; Hagos et al., 2009; Mengistie and Kidane, 2016). Hagos et al. (2009), assessed the impact of irrigation on household economic status, and found that irrigated households are getting about 323 US dollars per hectare, which is about 220 % higher than the expected income under the rain fed system. Gebregziabher et al., 2009 also found that households who do not have access to irrigation earn 50% less than the average income of the irrigators. Moreover, irrigated households get higher yield (i.e. 35 − 200%) than the expected yield under rain-fed systems (Amede et al., 2008). However, considering the spatial distribution of the farm profit and agricultural yield, households farming in close proximity of an irrigation dam are getting higher than those in more distance (Lire, 2005). This indicates, agricultural production and productivity is negatively correlated with the distance from the reservoir.

Reservoirs are seen as promising means to address water scarcity and solve the impacts of unreliable rainfall patterns (Strobl and Strobl, 2011). There are about 50,000 large dams (i.e. with a height of above 15 meters) and more than 16 million small dams constructed in the world (Nilsson, 2013). However, low return to the investment of large dams limits the participation of donor organizations (Turral et al., 2010). Considering the return to investment, small scale irrigation schemes are better than the large scale (You et al., 2011; Xie et al., 2014). Because, the construction cost of constructing reservoirs is prohibitively expensive (Petheram et al., 2016).

Though irrigation schemes improve a household's food security status (Amede et al., 2008), poorly conceived and planned irrigation infrastructures have negative social and environmental costs (de Fraiture et al., 2010). The installation of irrigation infrastructures increases the incidence of malaria and other water borne diseases (Amdihun, 2008; Kibret et al., 2008). The incidence of malaria is negatively correlated with the distance from the reservoir; and people who live in close proximity to the dam have a higher likelihood of being affected by malaria than those who reside or work far from the reservoir (Lire, 2005). Furthermore, the issue of equity is one of the prominent factors that have to be addressed in irrigation planning and implementation. A study in the upper Limpopo basin, Mozambique, on small scale irrigation found that high investment cost of irrigation excludes the poor from participation (Ducrot, 2015). Moreover, the installation of water storage structures leads to the displacement of people, lost productivity and unemployment (Tilt and Gerkey, 2016).

2.4.2. Spate irrigation systems

Spate irrigation is defined as "*a resource system, whereby flood water is emitted through normally dry wadis and conveyed to irrigable fields"* (Mehari et al., 2007). The main source of water is floods that originated from catchment areas. Spate irrigation is one of the oldest irrigation systems and has been practiced for more than 7000 years (Mehari et al., 2011). Spate irrigation involves harvesting flash floods originated from inundated dry river beds and spreading into farming, grazing, and/or (agro)forestry areas (Mehari et al., 2011; van Steenbergen et al., 2011). It is a unique water management practice that has been implemented in the arid and semi-arid dryland areas where evapotranspiration surpasses the annual rainfall (van Steenbergen et al., 2010). Globally, spate irrigation is implemented in more than 2.6 million hectares of land (Mehari et al., 2011).

Spate irrigation systems play a vital role in moisture stressed drylands where the development of other irrigation and water harvesting interventions are either expensive or constrained by capacity, technology, and physical availability (Komakech et al., 2011; Erkossa et al., 2014). While achieving positive climate outcomes, spate irrigation can help to reduce natural resource depletion, prevent community clashes, drive intensification of livestock crop production systems, and ultimately help to reduce poverty and food insecurity in the country (Zimmerer, 2011; Hagos et al., 2017). For instance, it supports the livelihood of 13 million marginalized, resource poor, and economically disadvantageous people in 20 countries (Mehari et al., 2011).

Spate irrigation improves the food security situation of the dwellers in the arid and semi-arid area (Hagos et al., 2014). The use of spate irrigation in Ethiopia significantly reduced poverty; and its impact is higher with modern spate systems (Hagos et al., 2017). Furthermore, transforming flash floods into usable resources in the arid area of China reduced the economic damages imposed by floods by 71.7% and increased the vegetation as well as irrigable area (Zhang et al., 2018). Another study by Alemayehu (2014), revealed that agricultural yield under spate irrigation system in Ethiopia is 10 times higher than the area under rain fed system (i.e. with the same farm input and management level). Furthermore, spate irrigation contributes 62% to the household income in the Raya valley of Ethiopia (Yazew et al., 2014a).

Despite the invincible potential and suitability of spate irrigation systems for topographic setting of dryland agro ecology (Mehari et al., 2007; van Steenbergen et al., 2010), less attention is given to it (Mehari et al., 2011). This is mainly due to risky characteristics of the spate irrigation system (van Steenbergen et al., 2011; Haile et al., 2013). The success of spate irrigation systems depends on the volume of floods diverted, which is highly unpredictable both in time, frequency, and volume (Mehari et al., 2007; van Steenbergen et al., 2010). Furthermore, the spate irrigation system is a risk prone practice. The floods could carry large sediment loads, which in return could either lift up the command area or incur additional cost of removing sediments (van Steenbergen et al., 2010).

2.4.3. Road-water harvesting

Investment in road-water harvesting, on one hand, is essential to reduce the impact of floods in roads, livelihoods of the community who live in the vicinity of the road, and farming plots (Puertas et al., 2014; Van Steenbergen et al., 2019). On the other hand, the construction of 'green roads' also enhances economic growth by utilizing the runoff water that drains into and/or out of the roads (Van Steenbergen et al., 2019). However, these benefits are neglected due to the implementation of the social infrastructures separately (Puertas et al., 2014; Demenge et al., 2015; Van Steenbergen et al., 2019). Thus, the 'Multifunctional approach' of road-water harvesting intervention is essential to reduce the negative impacts of road construction and optimize the benefits from water harvesting structure (Demenge et al., 2015).

Investment in water harvesting interventions increases household income, reduces food insecurity, and promotes sustainable development (Hatibu et al., 2006; Gebregziabher et al., 2009; Hanjra et al., 2009a, 2009b; Moges et al., 2011; Burney and Naylor, 2012; Hagos et al., 2012; Dile et al., 2013; Zhang et al., 2018). Because, water harvesting technologies significantly increases crop yield, improves factor productivity, creates employment opportunity, and reduces crop failure (Senkondo et al., 2004; Hatibu et al., 2006; Gebregziabher et al., 2009; Moges et al., 2011; Bouma et al., 2016; Hagos et al., 2017). The contribution of water harvesting is significantly higher in areas where majority of the people are reliant solely on rainwater, such as Sub-Saharan Africa (Senkondo et al., 2004; Hatibu et al., 2006; Molden et al., 2010; Hagos et al., 2013; Bouma et al., 2016).

The impact of road development on poverty and economic growth is well documented (c.f. Bryceson et al., 2008; Fan and Chan-Kang, 2008; Faiz et al., 2012; Acheampong et al., 2018; Aggarwal, 2018;). Roads enhance rural and urban market integration as well as improve access and mobility of people and goods (Demenge et al., 2015; Acheampong et al., 2018; Aggarwal, 2018). The market integration led farmers to use more farm inputs (Aggarwal, 2018), which in return increased agricultural productivity (Acheampong et al., 2018). Worku (2011) studies a macro economic impact of road sector development on the growth of Ethiopian economy; and revealed that expansion of road network influences the economic growth positively. However, at micro level, the ability of the people to benefit from expanding road networks is largely associated with their initial asset holdings (i.e. land and livestock) and existence of effective integrated development projects (Demenge et al., 2015). Moreover, the poverty reduction effect of expanding road networks varies with the type or grade of the road (Fan and Chan-Kang, 2008; Worku, 2011).

Although expansion of road network facilitates economic growth and development, it has also detrimental effect on the landscape, hydrology, and ecology of the areas (Forman and Alexander, 1998; Jungerius et al., 2002; Liu et al., 2008; Patarasuk and Binford, 2012; Puertas et al., 2014; Demenge et al., 2015). For example, reduction of forest, grass, farm, and shrub lands due expansion of road networks was observed in southwest China (Liu et al., 2008). The construction of roads affects the permanent and/or seasonal river flows, which in return compromises the livelihood of the population that lives in the vicinity of the roads (Jungerius et al., 2002; Puertas et al., 2014; Demenge et al., 2015).

2.5. Research gap

Climate change effects are worsening the already existing global level of poverty and food insecurity. This situation is even worse in Sub Saharan Africa where the majority of the people are dependent on subsistence farming systems and have limited climate change adaptation capacities. The global communities as well as individual countries are investing large sums of money in strengthening the adaptive capacity of the poor. Investment in rainwater and irrigation development is one of the promising interventions that increase the adaptive capacity of the poor as well as create climate resilient societies. Though there are some empirical studies carried out to assess the economic impacts of rainwater harvesting structures, these studies are mostly based on historical data (ex-post). In contrast, the ex-ante impact assessment of the rainwater harvesting and irrigation development interventions are limited. Furthermore, there are no prior studies that assessed the economic viability of an irrigation dam, road-water harvesting, and spate irrigation development interventions in Tigray region of Ethiopia and Turkana County of Kenya, respectively.

Most of the literature in the assessment of agricultural development interventions do not capture the uncertainty in forecasting projected outcomes. Because, scholars have limitations in identifying appropriate tools that enable them to capture uncertainty and parametric variability.

However, recent developments are adopting tools, such as Stochastic Impact Evaluation (SIE), to support decision making under a state of uncertainty and data scarce environment. Despite the wide applicability of SIE in other disciplines, there are no prior studies that applied the technique to evaluate large scale agricultural development interventions, such as rainwater and irrigation development interventions.

CHAPTER THREE: METHODOLOGY

This section is designed to describe the study area and case studies and elaborate the methodology applied based on the data paper that published at the *Data In Brief* journal[3]. The section presented all the approaches and steps used to conduct this study by taking an irrigation dam development intervention as an example.

3.1. Study area

In order to answer the research questions, the individual case studies were carried out in Tigray region of Ethiopia and Turkana county of Kenya (**Figure 3-1**). In the Tigray region, the economic viability of an irrigation dam development intervention as well as road-water harvesting interventions were evaluated. Whereas in Turkana, the economic viability of introducing a spate irrigation system was evaluated.

3.1.1. Irrigation dam construction intervention

The economic viability of an irrigation dam construction intervention was conducted at Ebo village of Raya Azebo district, which is situated in the southern part of Tigray. The government of Tigray had a plan of constructing an irrigation dam, with a water holding capacity of 6.3 million m^3. The dam is intended for an irrigation purpose, and expected to collect flood water from seasonal rivers (i.e. no permanent rivers in the area). The dam is located within the Raya Valley, which is an area identified as potential for different irrigation expansion by the regional government (Hagos, 2010; Haile et al., 2013; Yazew et al., 2014). The dam will lead to displacement of farmers as well as land use change (i.e. converting farming plots to reservoirs). The intervention will also affect the downstream non-irrigators by harvesting the water and storing it in the reservoir. Thus, the study evaluated this complex intervention for all the stakeholders affected by the construction of the dam.

[3] Based on: Yigzaw, N., Mburu, J., Ogutu, C.A., Whitney, C., Luedeling, E., 2019b. Data for the evaluation of irrigation development interventions in Northern Ethiopia. Data Br. 25. https://doi.org/10.1016/j.dib.2019.104342

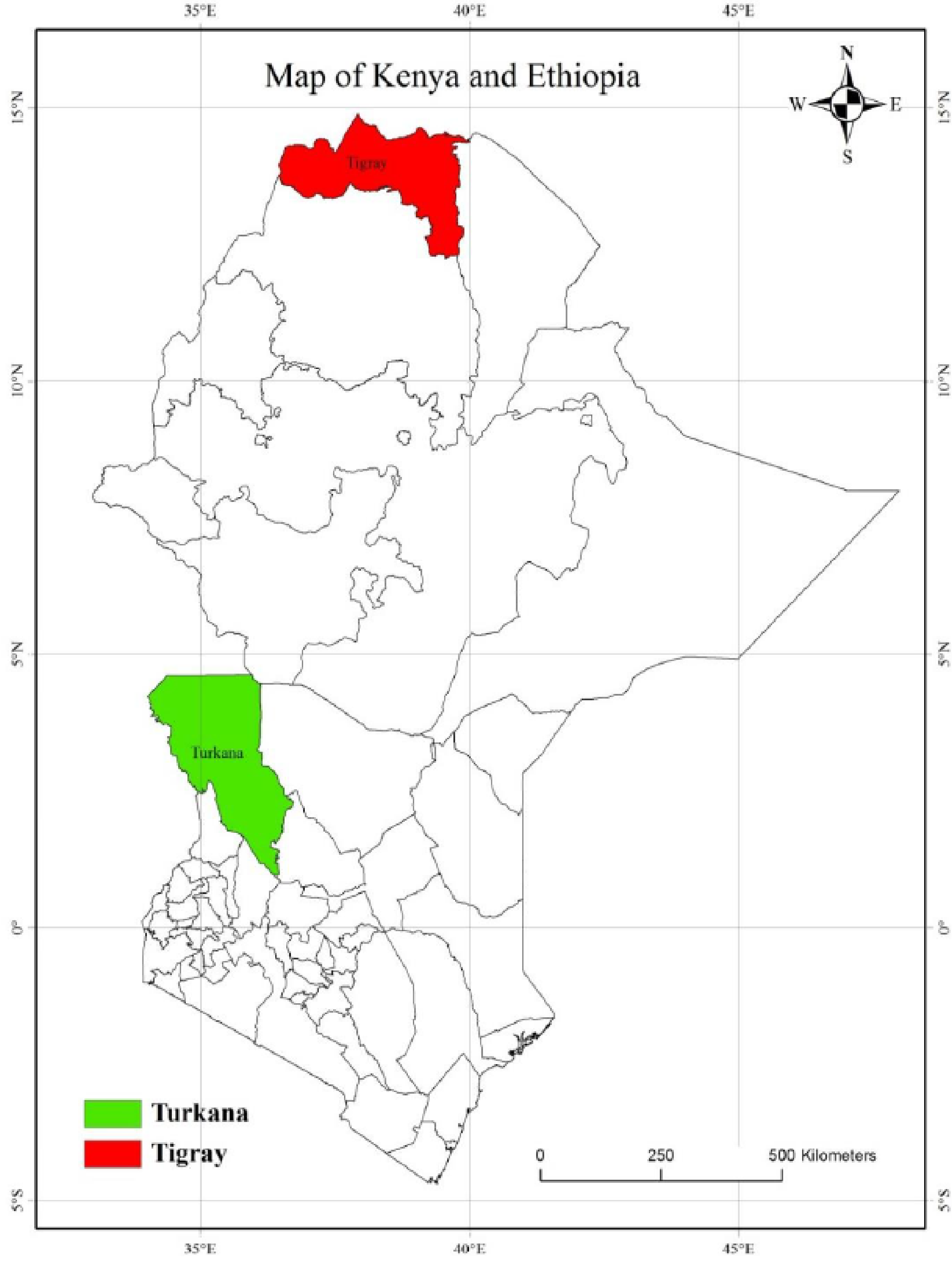

Figure 3-1: Map of the study area

3.1.2. Road-water harvesting intervention

Lack of climate-smart or green roads are compromising the ecological setting of the areas and affect the hydrological as well as economic wellbeing of the people who live in the vicinity of roads (Puertas et al., 2014). Because, the majority of the roads, especially in developing countries, were not considering the effect of climate extremes, such as flooding and increasing temperature during the planning phase. Accordingly, countries are spending a substantial amount of their budget in repairing and maintaining roads that are affected by floods. In Ethiopia, 35% and 60% of the damage on all weather and paved roads is related to flooding (World Bank, 2006). Integrating road network expansion with effective water harvesting structure is, therefore, essential for the improving social wellbeing of the societies (Demenge et al., 2015). Currently they are global efforts to integrate road-water harvesting interventions with road network expansion. However, little is known about the viability of these interventions. Therefore, this study evaluated the feasibility of different road-water harvesting structures in Tigray region of Ethiopia.

3.1.3. Spate irrigation intervention

The Turkana integrated development plan seeks to minimize drought and flooding impacts by investing in water harvesting technologies and irrigation development (Turkana County Government, 2013). The county is dominated by low lying (flat) open plains with mountain ranges (Yazew et al., 2014b), which is suitable for spate irrigation practices (c.f. Mehari et al., 2011; van Steenbergen et al., 2010). Though spate irrigation is new to the area, the potential bright spots for introducing spate irrigation systems in Turkana country had been assessed by Mekelle university (Yazew et al., 2014b). The topographic setting as well as rainfall status was taken into consideration during suitable site selection. Accordingly, nine potential sites were identified (i.e. Kaapus, Nakibuse, Kobuine, Lomidat-1, Lomidat-2, Natira (Lokipoto), Nakatwan, Kalapata, and Kospir). Thus, this study was carried out to identify the plausible costs, benefits, and risks of introducing spate irrigation systems into Turkana county, Kenya. This study further assessed the viability of introducing a spate irrigation system for two different spate systems (i.e. small spate irrigation that can irrigate 50 to 100 ha and large spate irrigation that can irrigate between 101 and 200 ha).

3.2. Model development

3.2.1. Sampling procedure

To develop an impact pathway model and collect quantitative estimates of the input parameters, the studies were guided by the decision analysis approach (Luedeling et al., 2015). The approach seeks to actively involve the local experts in the development of an impact pathway model. In this case, 'experts' refers to local knowledge holders with in-depth understanding of the local context and subject matter under study. The experts are nominated based on their potential to clearly articulate the proposed intervention and identify the potential benefits, costs and risks of the proposed intervention. To elaborate the steps, the procedure used to conduct an irrigation dam intervention study (i.e. objective one) was presented.

In order to identify the experts, a first contact and preliminary interview with the respective body is required. For an irrigation development intervention in Tigray region (i.e. objective1), model development was begun with an interview with the head of the region's irrigation development program who was the official coordinator of the intended project. This coordinator helped to identify the experts with knowledge of similar local systems. After identifying experts who are willing to participate, a decision model development workshop was organized. These experts were asked to consider the intervention decision and identify the main effects of the proposed project, which they grouped into factors of relevance to the local community (hereafter referred to as stakeholders), the environment, and the implementer. Then, the expected impacts were identified. For an irrigation dam intervention (objective one), the stakeholders were further classified into four groups: (i) downstream irrigators (farmers who would use the water from the dam for agriculture in an irrigation scheme), (ii) downstream non-irrigators (farmers downstream who could be affected by the dam but do not have access to the irrigation water), (iii) displaced farmers (those who currently live in the dam construction area but will need to be relocated and compensated, both financially and with a parcel of land in the irrigation scheme), and (iv) upstream non-irrigators (those who live upstream of the dam, close enough to access water for domestic use and/or livestock consumption). This classification was based on location and access to the irrigation scheme (i.e. the land with access to water from the irrigation project), After this, the preliminary qualitative impact pathway model based on local expert knowledge, including important costs, benefits, and risks of the project for the stakeholders, the implementer and the environment was generated. This preliminary model was then shared with the experts for review and refined based on their feedback. We, then, consolidated all inputs and developed the final impact pathway of the proposed intervention, which reflected the current state of understanding and knowledge of all experts (Luedeling et al., 2015).

3.3. Model parametrization

Experts provided quantitative estimates for all model variables covering the benefits, costs and risks of the proposed intervention. Expert knowledge elicitation approach, which is also used in other studies (Luedeling et al., 2015; Whitney et al., 2018, Lanzanova et al., 2019), was used to collect estimates for model variables. Before collecting qualitative estimates, a calibration training (Hubbard, 2014) was provided to all experts. All experts were then familiarized with estimation techniques to overcome bias, allowing them to provide quantitative estimates in the form of distributions representing their subjective 90% confidence intervals (Wafula et al., 2018). The difference between the upper and lower limit in each range of value indicates our (analysts and experts) level of calibrated uncertainty for the specified parameter. Initial monetary estimates were collected in local currency and converted to US dollars at the existing exchange rate during the data collection. The exchange rate applied for all case studies were integrated in the estimate table. The experts provided an estimate and distribution type for all identified parameters.

3.4. Data analysis

Stochastic impact evaluation tools: Monte Carlo simulation, Partial Least Squares regression, and Value of Information analysis (Luedeling et al., 2015; Whitney et al., 2017) was used to project the outcome of the proposed intervention, identify the sensitive variables that influence the distribution of the decision outcomes, and identify critical knowledge gaps that may change the emerging decision recommendations, respectively.

The proposed intervention should be considered as a business case scenario to clearly model the impact pathway model. For example, the dam construction intervention was modeled in two ways: 1) dam construction complemented with catchment restoration; and 2) dam construction without catchment restoration. The model computes the marginal benefits and losses of implementing the proposed project by subtracting the total expected costs from the expected benefit. The expected total benefit is the sum of all additional benefits, such as crop production and employment opportunities, obtained from the implementation of the project (i.e. with project) and the benefit of reducing losses or damages, like flooding effect, by having the dam (i.e. the reduction of costs incurred under 'the business as usual scenario'). The total expected cost is also computed by adding up all the additional costs incurred by having the dam, such as agricultural production costs, costs of displacement, project costs (i.e. with project), and the benefit forgone (under the 'business as usual') by having the structure, including the productivity lost and negative environmental effects.

3.4.1. Monte Carlo Simulation

The resulting model was scripted in the R programming language (R Core Team, 2018). The 'decisionSupport' package (Luedeling and Göhring, 2018) was used and run the model 10,000 times as a Monte Carlo simulation to randomly select values from defined distributions for all input variables (Arnold and Yildiz, 2015). Monte Carlo simulation works by randomly selecting values from the specified range of values, which follows a predefined distribution of the parameter, and computes the expected output deterministically. The model was used to provide forecasts of the costs, benefits and risks of the irrigation project for each stakeholder, the implementer, and the environment. The forecasted marginal benefits/losses were discounted according to an estimated discount rate to compute the monetized net benefit, expressed as net present value (NPV). NPV represents the sum of discounted projected net benefits over the expected life span of the project (Luedeling et al., 2015). The NPV for all the stakeholders, the implementer and the environment were computed. In order to guide the decision, the total project outcome (i.e. the sum of NPVs for all stakeholders, the implementer and the environment) was computed.

NPV represents the sum of discounted projected net benefits over the expected life span of the project. For the dam construction intervention, the NPV was computed for all the stakeholders, the environment and the implementer, and these NPVs were aggregated to compute the overall outcome of the proposed irrigation dam project. Mathematically the total project NPV is;

$$NPV = \sum_{i=1}^{6} \sum_{t=1}^{30} \frac{C_{it}}{(1+r)^t}$$

where, i is the expected group to be affected by the proposed intervention (e.g. i=1 for downstream farmers, 2 for displaced farmers), t is the time of the cash flow, r is the discount rate used, and C_{it} is the risk-adjusted net cash flow for the expected group i at time t (i.e. the difference between the risk-adjusted total benefits for the expected group i at time t and the risk-adjusted total costs for the expected group i at time t).

3.4.2. Partial Least Squares regression

The sensitive parameters that strongly influence the simulated outcome were identified using Partial Least Squares (PLS) regression. PLS identifies linear combinations of the input variables that explain variation in a dependent variable based on the principle of variable compression (Luedeling and Gassner, 2012). PLS was used to regress the NPV of the proposed project outcomes against the all input variables. The variables were selected based on the Variable of Importance in projection (VIP) score. All variables above the value of 0.8 are considered as influential variables.

3.4.3. Value of Information analysis

I identified the variables with highest value of information (i.e. variables that most influence the sign of the project outcome) using Value of Information (VoI) analysis (Tuffaha et al., 2016). I used the expected value of perfect information (EVPI) procedure described by Wafula et al. (2018), to calculate the monetary value of additional information for the decision-making process. The EVPI is the difference between the expected outcome of the proposed intervention under perfect information and the expected outcome of implementing the proposed intervention under current information. Mathematically EVPI is;

$$EVPI = EV_{wPI} - EV_{woPI}$$

Where EVPI is the expected value of perfect information, EV_{wPI} is the the expected value of a decision with perfect information, and EV_{woPI} is the expected value of a decision without perfect information. EVPI indicates the maximum value that a decision maker should be willing to pay in order to reduce uncertainty about which decision alternative promises the greatest returns (Whitney et al., 2017).

3.5. Data

The data that was used for the holistic ex-ante impact evaluation of the proposed intervention was collected from the experts. These data were saved in excel. The data used for the studies were in the appendices section (Annex A-4 to A-6). Sample data from the irrigation dam intervention is presented in the table below (**Table 3-1**) to show the data structure. The data should capture all important impact parameters (i.e. expected benefits, costs, and risks) of the proposed intervention. In order to run the model, we need to have an estimate sheet, correlation matrix (i.e. if any), and legend for all parameters. The estimate sheet has the lower and upper values as well as the type of distribution for each parameter (**Table 3-1**). The legend table is used to translate the variable names used in the R-programming language into readable figure labels.

Table 3-1: List of sample parameters identified by the experts for an irrigation dam construction, their corresponding estimates, and distribution type

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Expected life of the dam (i.e. simulation period)	30	30	const
Coefficient of variation introduced for water allocation	10	20	posnorm
General coefficient of variation	5	10	posnorm
Farmers discount rate	15	20	posnorm
Discount rate (Implementer)	10	10	const
Construction duration (years)	2	2	const
Water holding capacity of the dam	4,500,000	6,500,000	posnorm
Water loss due to evaporation (as percentage of the dam water holding capacity)	4	8	posnorm
Water percolate into the ground (as percentage of the dam's water holding capacity)	0.5	1	posnorm
Water loss due to seepage (as percentage of the dam's water holding capacity)	0.3	1	posnorm
Crop water requirement	4,500	7,000	posnorm
Loss of water due to irrigation inefficiency	0.4	0.6	posnorm
Maximum area suitable for irrigation (i.e. area that has an irrigation structure)	350	405	posnorm
Years without fruit production after plantation	4	7	posnorm
Time from planting until maximum fruit yield (years)	10	15	posnorm
Fruit (mango, orange...) initial productivity per hectare (ton)	3	6	posnorm
Maximum attainable fruit yield	10	16	posnorm
Proportion of area for fruit production	0.15	0.3	tnorm_0_1
Fruit price per ton	10000	20000	posnorm
Time to reach a maximum crop harvest (years)	5	10	posnorm
Initial vegetable (onion and tomato) productivity per hectare (ton)	12	15	posnorm

Distribution type: posnorm is positive normal distribution, const is constant and tnorm_0_1 is truncated normal distribution between the value of zero and one. These parametrs are randomly selected from the total list of parameters.

CHAPTER FOUR: STOCHASTIC IMPACT EVALUATION OF AN IRRIGATION DEVELOPMENT INTERVENTION IN NORTHERN ETHIOPIA[4]

Abstract

Irrigation plays a significant role in achieving food and nutrition security in dry regions. However, detailed *ex-ante* appraisals of irrigation development investments are required to efficiently allocate resources and optimize returns on investment. Due to the inherent system complexity and uncertain consequences of irrigation development interventions coupled with limited data availability, deterministic cost-benefit analysis can be ineffective in guiding formal decision-making. Stochastic Impact Evaluation (SIE) helps to overcome the challenges of evaluating investments in such contexts. In this paper, SIE was applied to assess the viability of an irrigation dam construction project in northern Ethiopia. Expert knowledge was elucidated to generate a causal model of the planned intervention's impact pathway, including all identified benefits, costs and risks. Estimates of the input variables were collected from ten subject matter experts. I then applied the SIE tools: Monte Carlo simulation, Partial Least Squares regression, and Value of Information analysis to project prospective impacts of the project and identify critical knowledge gaps. Model results indicate that the proposed irrigation dam project is highly likely to increase the overall benefits and improve food and nutrition status of local farmers. However, the overall value of these benefits is unlikely to exceed the sum of the investment costs and negative externalities involved in the intervention. Simulation results suggest that the planned irrigation dam may improve income, as well as food and nutrition security, but would generate negative environmental effects and high investment costs.

Keywords: Reservoir construction, food security, investment feasibility, ex-ante appraisal, water harvesting, decision support.

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[4] Based on: Yigzaw, N., Mburu, J., Ackello-Ogutu, C., Whitney, C., Luedeling, E., 2019a. Stochastic impact evaluation of an irrigation development intervention in Northern Ethiopia. Sci. Total Environ. 685, 1209–1220. *https://doi.org/10.1016/j.scitotenv.2019.06.133*

4.1. Introduction

Many African farmers are poor, vulnerable and marginalized (UN, 2015). Land degradation and frequent extreme weather events (e.g. droughts and floods) are among the many causes of low agricultural productivity, poverty and food insecurity on the continent (Brown et al., 2011; Shiferaw et al., 2014; Solh and Van Ginkel, 2014; Lewis, 2017). Understanding local social, economic, and ecological systems will be necessary for increasing land productivity to meet food security needs and increase future resilience of agricultural systems in the region (Rosenstock et al., 2014; Solh and Van Ginkel, 2014). Irrigation is one option for improving national food and nutrition security and to increase farmers' resilience to climate change, especially in arid regions (Gebregziabher et al., 2009; Hanjra et al., 2009a, 2009b; Namara et al., 2010; Calzadilla et al., 2013; Wossen et al., 2014). Effective agricultural water management also plays a considerable role in enhancing agricultural production and productivity. This in turn contributes to reducing poverty, stabilizing household income, and improving the nutritional and health status of the community (Gebregziabher et al., 2009; Hagos et al., 2009; Namara et al., 2010).

In Africa, the dominant farming strategy is subsistence-oriented rain-fed agriculture characterized by "low-input /low-output" practices (AGRA, 2014). Expansion of agricultural irrigation has been proposed as a potential strategy for reducing food insecurity (You et al., 2011; Xie et al., 2014) and increasing household income (Gebregziabher et al., 2009; Hagos et al., 2009; Hanjra et al., 2009a, 2009b). Despite the potential benefits of irrigation in Africa, only around seven percent (~ 15 million hectares) of the continent's total arable land is equipped for irrigation, far below the global average of 23.4% (FAOSTAT, 2014). In recent decades, irrigation areas have been expanding at an average rate of 2.3% annually (You et al., 2011), and they are expected to expand by around 24 million hectares over the next five decades (You et al., 2011). Xie et al. (2014) estimated that in Sub-Saharan Africa, 30, 24, 22, and 20 million hectares of irrigable area could be developed through motorized water pumps, treadle pumps, small reservoirs, and communal diversions, respectively.

In Ethiopia, less than five percent of the total irrigation potential is utilized (Awulachew et al., 2007; You et al., 2011; Xie et al., 2014). This is due to under-performance of operational irrigation schemes, resource constraints, poor rural infrastructure, limited governmental commitment to the sector, lack of integration between different governmental sectors or stakeholders that share common irrigation development objectives, and a shortage of planned irrigation development projects (i.e. both in number of projects and targeted irrigable area) (Awulachew et al., 2010; You et al., 2011). Cognizant of the potential, the Ethiopian government is considering expansion of irrigation as a priority investment to reduce food insecurity and poverty (Awulachew et al., 2007; Hagos et al., 2009; MoARD, 2010).

Irrigation potential can be expanded by investing in large-scale dams and/or small-scale irrigation developments (You et al., 2011). Dam-based irrigation expansion is a common practice in Ethiopia. For example, over the last two decades, about 100 dams were constructed in the Tigray region, with more than three quarters of the structures dedicated exclusively to irrigation (Berhane et al., 2016). However, researchers disagree which kind of irrigation development delivers the highest return on investment. Some expect greater impacts on food security from dams, since they allow establishment of large cropping areas (e.g. Strobl and Strobl, 2011), while others have argued that small-scale structures are more effective and sustainabale, as well as less harmful to the environment (e.g. You et al., 2011; Dile et al., 2013).

4.1.1. Stochastic Impact Evaluation of irrigation development projects

Agricultural development intervention decisions are mostly based on perceived economic and technical viability (e.g. Dadaser-Celik et al., 2009; Balana et al., 2012), yet they have social, political, and environmental impacts (Luedeling et al., 2015). In addition, the complex nature of agricultural development interventions such as irrigation dams and their long-term consequences (Kalra et al., 2014), coupled with uncertainty and variability of important parameters, limits decision-makers' ability to clearly anticipate project impacts (You et al., 2011; Xie et al., 2014; Li et al., 2016). Furthermore, in developing regions such as Sub-Saharan Africa, data scarcity hinders decision makers' ability to make informed decisions (Luedeling et al., 2015; Shepherd et al., 2015; Luedeling and Shepherd, 2016). The uncertainties and variabilities in an irrigation dam range from the hydrological and agronomic parameters to socioeconomic, environmental and social dimensions (Graveline et al., 2012; Li et al., 2016). These uncertainties and variabilities are rarely considered in development project evaluations (Rosenstock et al., 2014; Luedeling et al., 2015), but they substantially limit the usefulness of the commonly used approach of deterministic cost-benefit analysis, which cannot easily handle imprecise information (Luedeling et al., 2015; Luedeling and Shepherd, 2016). Failure to comprehensively consider all project outcomes and their inherent uncertainty and variability can jeopardize project success or lead to undesirable outcomes (Rosenstock et al., 2014; Luedeling et al., 2015). Therefore, a detailed *ex-ante* appraisal is required to allocate resources efficiently and to optimize the returns of agricultural development investments.

Stochastic Impact Evaluation (SIE) is an *ex-ante* appraisal approach that allows integration of different impact dimensions by considering the intervention as a business case and by capturing the variability and uncertainty of all input variables (Luedeling et al., 2015; Luedeling and Shepherd, 2016). SIE is a probabilistic decision modeling approach (Wafula et al., 2018), which is suitable for evaluating the outcomes of development projects, even when data availability is limited (cf. Rosenstock et al., 2014; Luedeling et al., 2015; Whitney et al., 2017). However, despite its potential, it has rarely been applied to agricultural development interventions (Luedeling et al., 2015). I applied the decision analysis tools: Monte Carlo simulation, Partial Least square regression, and Value of Information analysis (Luedeling et al., 2015; Whitney et al., 2017) to project the outcome of the proposed intervention, identify the sensitive variables that influence the distribution of the outcome and to identify critical knowledge gaps.

My aim was to apply SIE to assess the economic viability of an irrigation development project in northern Ethiopia in terms of monetized overall benefits, as well as food and nutrition security indicators for all major stakeholder groups and the environment both with and without catchment restoration practices. I use the value of information concept to identify critical uncertainties that strongly influence the model and may be targeted for further decision-supporting (Luedeling et al., 2015; Whitney et al., 2017).

4.2. Methods

4.2.1. The study area

The study area is located in the Tigray region of Ethiopia, where I investigated the regional government's decision to build an irrigation dam at Ebo village, in the Raya-Azebo Wereda (district) of Southern Tigray. The proposed dam construction site is located at 39.63° to 39.66° E and 12.86° to 12.89° N (**Figure 4-1**). The planned dam is expected to be 35 m high and 6 m thick, with a crest length of 700 m. It is expected to hold up to 6.3 million cubic meters of water and irrigate around 405 ha of farmland (Tesfay, 2017). Considering the average size of land holdings in the study area: 0.5 to 0.6 ha (Yazew et al., 2014a), the dam could support an irrigation scheme large enough to provide water to about 675 to 810 farmers.

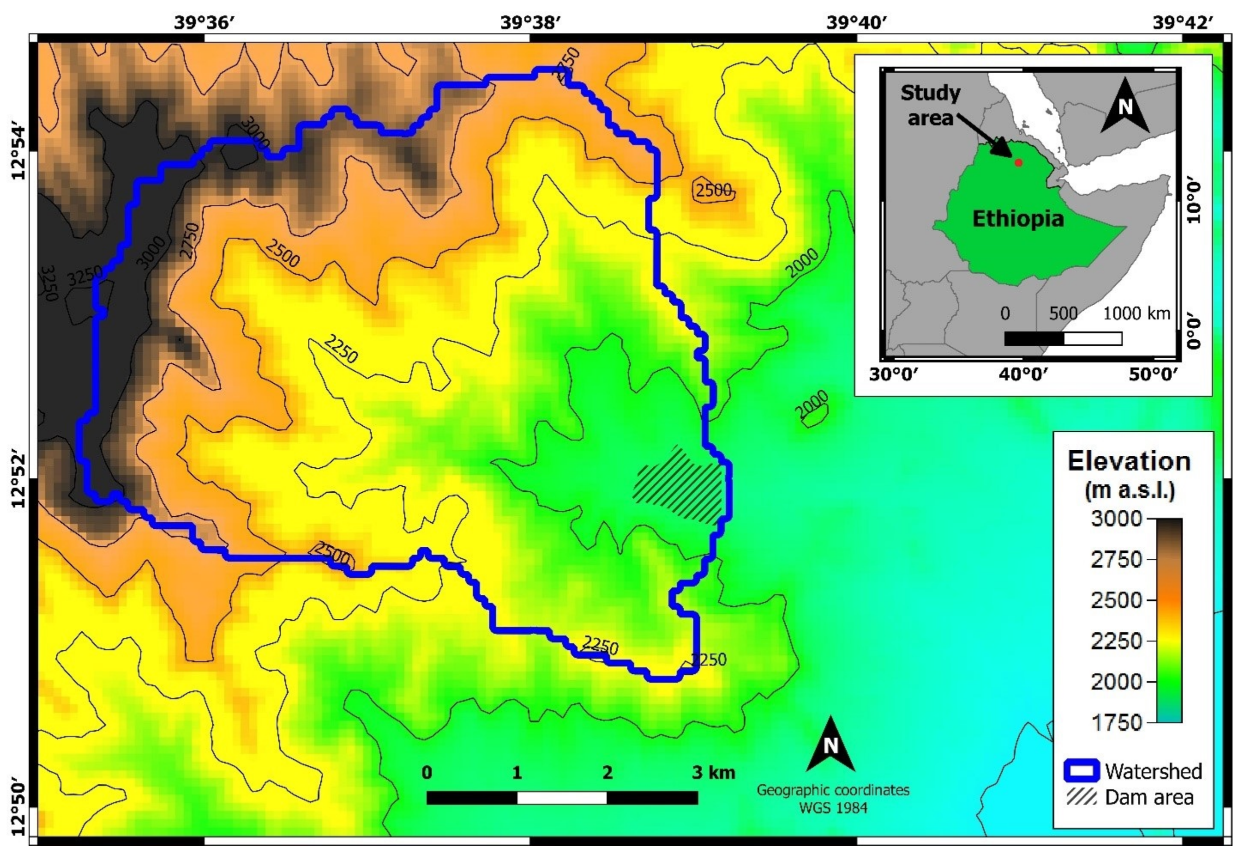

Figure 4-1: Study region and dam construction site in Tigray, Ethiopia.

The blue line represents the edge of the watershed area (32.24 km^2*), blue cross hatch (center) represents the expected flooded dam area.*

The study area is semi-arid with a bimodal rainfall distribution, characterized by a short rainy season between March and April and a long rainy season from July to September (Hagos, 2010). The altitude of the study area ranges from 1370 m in the lowlands up to 3600 m a.s.l. on the region's mountain peaks and plateaus (**Figure 4-1**). Due to these differences in elevation, mean annual rainfall ranges from 350 mm in the lowlands to 800 m in mountainous areas (Hagos, 2010; Haile et al., 2013; Yazew et al., 2014). The study region has no permanent rivers, so the proposed reservoir will rely on intermittent floods created by heavy rains in the catchment area.

The majority of the local population relies on crop and livestock farming for their livelihoods (Hagos, 2010; Yazew et al., 2014). Raya Valley, which includes the proposed dam area, is considered a high-potential location for irrigation expansion by the regional government (Hagos, 2010; Haile et al., 2013; Yazew et al., 2014).

4.2.2. Participatory model development and parametrization

To develop and parametrize a model of the dam construction decision, I followed a decision analysis approach (Luedeling et al., 2015). The approach seeks to actively involve local experts in development of both an impact pathway and a final decision model. In this case, 'experts' refers to local knowledge holders with in-depth understanding of the local context and the potential benefits, costs and risks of dam construction.

Model development began with an interview with the head of the region's irrigation development program, the official who would be the coordinator of the intended project. This coordinator helped to identify ten experts with knowledge of similar local systems: two experts in engineering projects (hydraulic and design), one in socioeconomic systems, two in agronomic systems, three in watershed and environmental management, and two in water supply systems. These ten experts were asked to consider the dam construction project decision and identify the main effects of the proposed project, which they grouped into factors of relevance to the local community (hereafter referred to as stakeholders), the environment, and the implementer. Based on location and access to the irrigation scheme (i.e. the land with access to water from the irrigation project), the stakeholders were further classified into four groups: (i) downstream irrigators (farmers who would use the water from the dam for agriculture in an irrigation scheme), (ii) downstream non-irrigators (farmers downstream who could be affected by the dam but do not have access to the irrigation water), (iii) displaced farmers (those who currently live in the dam construction area but will need to be relocated and compensated, both financially and with a parcel of land in the irrigation scheme), and (iv) upstream non-irrigators (those who live upstream of the dam, close enough to access water for domestic use and/or livestock consumption).

We generated a preliminary qualitative impact pathway model based on local expert knowledge, including important costs, benefits, and risks of the project for the stakeholders, the implementer and the environment. This preliminary model was then shared with the experts for review and refined based on their feedback. Moreover, the identified environmental impact was further refined based on existing literature. I consolidated all inputs into a final model capturing the impact pathway of the proposed intervention, which reflected the current state of understanding and knowledge of all experts (Luedeling et al., 2015).

Experts provided quantitative estimates for all model variables covering the benefits, costs and risks of the dam construction (see **Annex 6-4**). I used an expert knowledge elicitation approach (Tamene et al., 2011; Luedeling et al., 2015; Whitney et al., 2017, 2018) to collect estimates for model variables. All experts were familiarized with estimation techniques to overcome bias, allowing them to provide quantitative estimates in the form of distributions representing their subjective 90% confidence intervals for model variables (Rosenstock et al., 2014; Luedeling et al., 2015; Wafula et al., 2018). Initial monetary estimates were collected in Ethiopian currency (i.e. Birr) and converted to USD at the Ethiopian National Bank's October 10, 2017 rate of $1=23.3908 ETB (NBE, 2017).

The resulting model was scripted in the R programming language (R Core Team, 2018) and run 10,000 times as a Monte Carlo simulation to randomly select values from defined distributions for all input variables (Arnold and Yildiz, 2015) using the 'decisionSupport' package (Luedeling and Göhring, 2018). The intervention was modeled in two ways: 1) the dam construction is complemented with catchment restoration; 2) the dam construction is implemented without catchment restoration. The model was used to provide forecasts of the costs, benefits and risks of the irrigation project for each stakeholder, the implementer, and the environment. The forecasted marginal benefits/losses were discounted according to an estimated discount rate to compute the monetized net benefit, expressed as net present value (NPV), representing the sum of discounted projected net benefits over the expected life span of the project (Luedeling et al., 2015). More information about the computation of the marginal benefits/losses is provided in chapter 3, methodology part, which is also published at the *Data In Brief* journal (Yigzaw et al., 2019b). In order to guide the decision, I also computed the total project outcome (i.e. the sum of NPVs for all stakeholders, the implementer and the environment).

4.2.3. Nutrition analysis

I used the model to forecast the additional total energy and pro-vitamin A that may become available for local people (cf. Whitney et al., 2017). Energy and pro-vitamin A outcomes were expressed according to the number of people whose annual needs could be covered by the additional agricultural production expected within the proposed irrigation scheme. These were computed by dividing the total energy and pro-vitamin A by the annual per capita requirements. Values for energy (in Kcal) and pro-vitamin A content (in mcg Retinol equivalent) per ton of yield as well as the per capita requirements of these measures were obtained from Whitney et al. (2017). Note that these calculations only consider the gross nutrient production, without accounting for factors such as food distribution or access.

4.2.4. Sensitivity analysis

Sensitive parameters within the model were identified by applying Partial Least Squares (PLS) regression (Wold et al., 1993; Luedeling et al., 2015), in which the NPV for each dimension of the model outcome was regressed against latent factors consisting of linear combinations of the input variables (Luedeling and Gassner, 2012). The selection of the most sensitive variables was done based on variable importance in the projection (VIP) calculation (Wold et al., 1993; Farrés et al., 2015). The VIP score measures the influence of an individual variable on the NPV of the proposed intervention (Akarachantachote et al., 2014; Farrés et al., 2015). Variables with a VIP score above 0.8 (Luedeling et al., 2015) were considered as influential variables. For these variables, I also determined whether they had a positive or negative influence on project outcomes.

4.2.5. Value of Information analysis

I identified the variables with highest value of information (i.e. variables that most influence the sign of the project outcome) using Value of Information (VoI) analysis (Tuffaha et al., 2016). These are the variables for which further measurement (reduction of uncertainty) could improve certainty about whether model outcomes are positive or negative (Luedeling et al., 2015). I used the expected value of perfect information (EVPI) procedure described by Wafula et al. (2018), to calculate the monetary value of additional information for the decision-making process. EVPI indicates the maximum value that a decision maker should be willing to pay in order to reduce uncertainty about which decision alternative promises the greatest returns (Whitney et al., 2017).

4.3. Results

Expert inputs were consolidated into a decision model with 175 variables (i.e. estimates and distributions of the benefits, costs and risks of the proposed intervention and some other nutritional and technical model parameters), which illustrated the expected impact pathway for the dam intervention (overview in **Figure 4-2**). The experts identified nine benefits, fourteen costs, and ten risks of the proposed dam intervention, when it is complemented with catchment restoration (**Table 4-1**). The plausible cost and benefit components for each of the stakeholders, the implementer, and the environment are illustrated in. Descriptions of all input variables used in the study and their estimates are provided in chapter 3 (see **Table 3-1**).

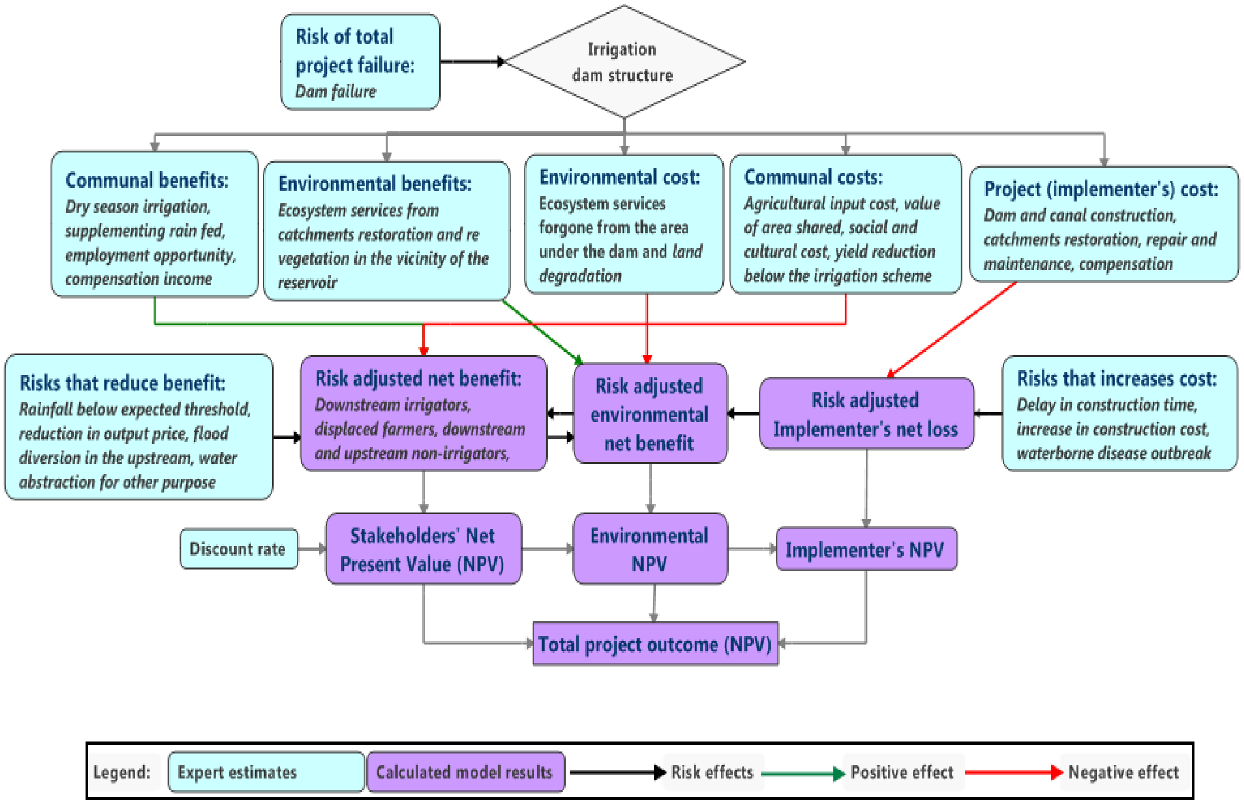

Figure 4-2: Causal impact pathway model representing the structure of the decision to implement an irrigation dam project in Tigray, Ethiopia.

The model represents important costs, benefits, and risks identified by local experts. The model is structured as an impact pathway from the decision to build the dam (top) through all estimated and risk-adjusted costs and benefits to the final model outputs in the form of Net Present Value (NPV). In this impact pathway model, I list some of the costs, benefits and risks of the proposed dam construction intervention. For all the identified costs, benefits and risks as well as corresponding impact on the stakeholder, the environment, and the implementer see ***Table A-1*** *in the appendices section.*

Experts identified irrigation as the primary purpose of the dam, including fully irrigated as well as rain-fed areas, which may benefit from supplemental irrigation during dry spells. The dam is also expected to create employment for the local community. The irrigation area will be planted with fruit trees, vegetables, groundnuts, and maize with cereal crops grown intensively in the rainy season (except in the area under fruit trees).

The proposed irrigation dam construction intervention will create both positive and negative secondary effects, and the impact depends on whether the dam is constructed with or without catchment restoration. The positive environmental effects (i.e. benefits) are the ecosystem services obtained from an increase in vegetation cover around the dam and within catchment area (i.e. if dam construction is complemented with catchment restoration). Environmental costs are ecosystem services that will no longer accrue because of the proposed intervention. These environmental costs arise from the reduction in vegetation cover further downstream of the dam (i.e. land degradation) and from ecosystem services currently produced by the area that will be submerged. The environmental impact of the intervention is, thus computed based on the ecosystem value of the change in vegetation cover, which composed of provisioning services (e.g. production of grass, fuelwood, and medicinal plants), regulating and maintenance services (e.g. improved microclimate, nutrient cycling, erosion control and sediment retention, carbon sequestration and habitat conservation), and cultural services.

The implementer of the project (i.e. the government) will cover the costs of constructing the dam and the canals, managing the catchment area through construction of soil conservation structures, reforestation, and area exclosure, and providing repair and maintenance. The residents of one village, called Mahgo, would need to be relocated because their homes are within the flooded area. The implementer will compensate the farmers for the loss of their homes and farming plots and after completion of the dam, the farmers will receive a plot within the proposed irrigation scheme. I modeled the net value (i.e. the difference between the compensation and the value farmers can generate without the dam) of the compensation as income.

Table 4-1: List of important costs, benefits, and risks of an irrigation dam construction

All identified impacts of the proposed dam construction	Dam construction with catchment restoration	Dam construction without catchment restoration
Benefit of the poposed project		
• Dry season irrigation	Yes	Yes
• Supplementing rainfed agriculture during unexpected dry spells in the rainy season	Yes	Yes
• Employment generation	Yes	Yes
• Income from compensation payments	Yes	Yes
• Time savings (fetching water and watering livestock)	Yes	Yes
• Access to better infrastructure	Yes	Yes
• Flood control	Yes	Yes
• Ecosystem services from catechment restoration (provisioning, regulating and maintenance, and cultural services)	Yes	No
• Ecosystem services from revegeation in the vicinity of the reservoir (provisioning, regulating and maintenance, and cultural services)	Yes	Yes
Cost of the proposed project		
• Dam and infrastructure construction (including study, design, monitoring and supervision)	Yes	Yes
• Catchment restoration (soil conservation, reforestation, and area exclosure)	Yes	No
• Compensation (for farming plot, house and public infrastructure)	Yes	Yes
• Repair and mainteinance	Yes	Yes
• Inputs for agricultural production	Yes	Yes
• Additional expenses (e.g. bills for utilities) for displaced farmers who pay for access to new infrastructure	Yes	Yes
• Residence construction (for displaced farmers)	Yes	Yes
• Social and cultural cost of displacement	Yes	Yes

All identified impacts of the proposed dam construction	Dam construction with catchment restoration	Dam construction without catchment restoration
• Loss of agricultural production during construction	Yes	Yes
• Yield reduction further downstream by holding water in the reservoir and catchment	Yes	Yes
• Reduction in alluvial deposits	Yes	Yes
• Value of farming area lost to the splitting up between settled and displaced farmers	Yes	Yes
• Ecosystem services forgone from the area under the dam	Yes	Yes
• Ecosystem services forgone from land degradation (i.e. reduction in vegetation, grass, and forest land) due to water storage	Yes	Yes
Risk of the proposed project		
• Delay in construction time	Yes	Yes
• Increase in construction cost	Yes	Yes
• Dam failure	Yes	Yes
• Occurence of dry spell	Yes	Yes
• Rainfall shortage (i.e. below the expected minimum threshold)	Yes	Yes
• Flood water diversion into another farming area before it reaches the dam	Yes	Yes
• Water abstraction by the municipality for supplying a nearby town	Yes	Yes
• Water abstraction for domestic and livestock consumption by farmers	Yes	Yes
• Reduction in selling price of farm products due to excess supply	Yes	Yes
• Increase in malaria incidence	Yes	Yes
• Sedimentation	No	Yes

List of important costs, benefits, and risks identified by the experts for an irrigation dam construction with and without catchment restoration projects in Tigray, Ethiopia. 'Yes' is considered and 'No' is not considered.

4.3.1. Projected irrigation development outcomes

4.3.1.1. Expected Net Present value (NPV)

The results of the Monte Carlo simulation show substantial variation in NPV but generally suggest a high likelihood of positive outcomes for all local stakeholders and negative outcomes for the environment and the implementer, when the dam is not complemented with catchment restoration. However, when the dam construction is complemented with catchment restoration, the outcome for the majority of stakeholders is higher and the environmental outcome becomes positive (**Figure 4-3**). The aggregated total project outcome was mostly negative both with and without catchment restoration, though the total loss reduced by accompanying catchment restoration measures.

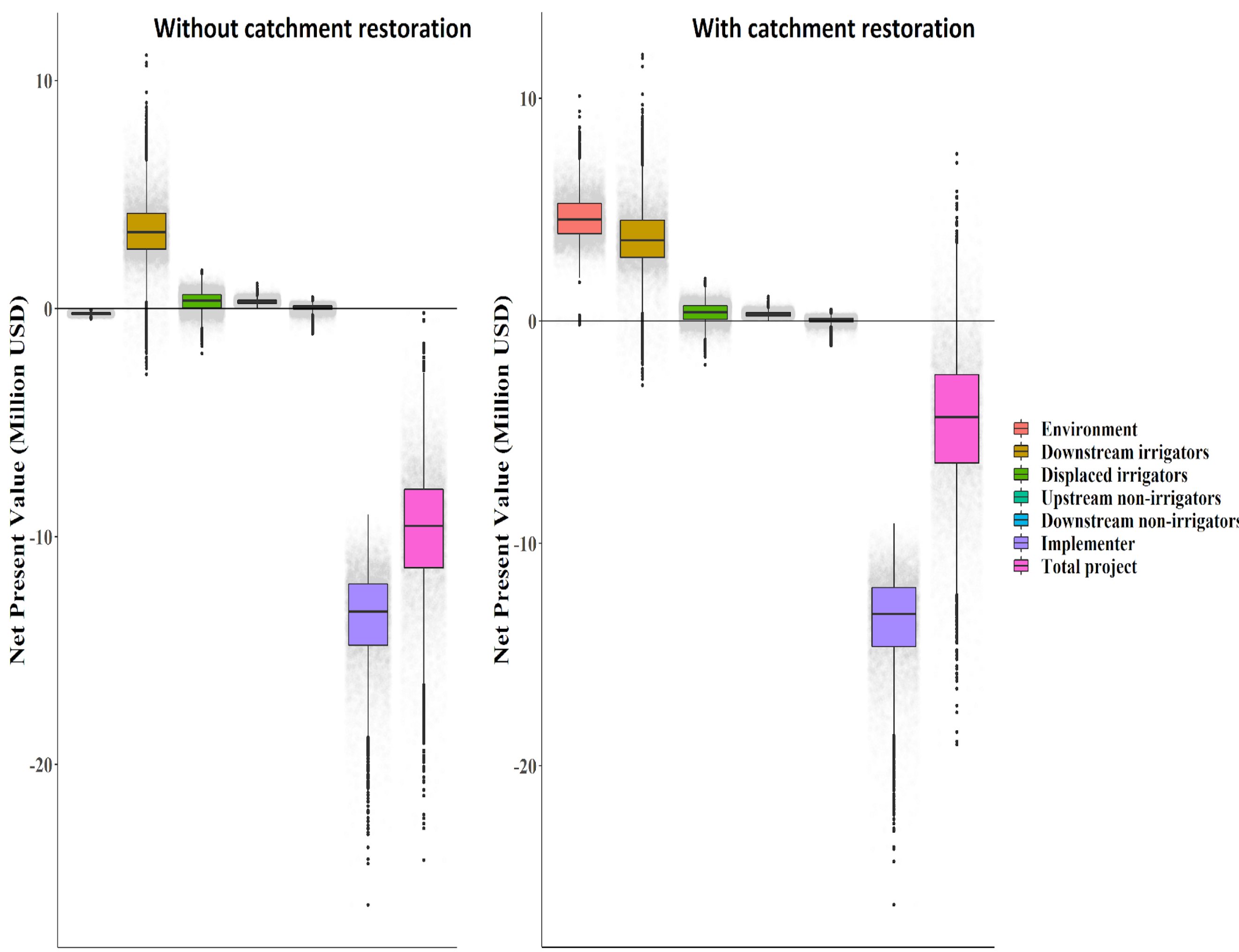

Figure 4-3: Distribution of the projected NPV for all the stakeholders, the implementer, and the environment for implementing an irrigation dam in Tigray.

Both the downstream and displaced farmers who stand to benefit from the use of irrigation provided by the dam tended to benefit from the intervention (i.e. with catchment restoration) with positive NPV in 97.74% and 79.14% of model runs respectively (see appendices: **Table A-2**). Farmers without access to irrigation also had a positive NPV in most cases (67.7% of model runs for downstream and 100% for upstream non-irrigators). NPV was highest for downstream irrigators (i.e. between $1.39 and $6.16 million, with a median value of 3.62 million), followed by displaced farmers, upstream non-irrigators, and downstream non-irrigators (**Figure 4-3**). The environmental outcome was mostly positive (99.75%) with NPV between $3.13 and $6.14 million and median NPV of $4.56 million. However, when dam construction was not complemented with catchment restoration, the likelihood of generating negative NPV increased for the majority of stakeholders and for the environmental outcome (see appendices: **Table A-3)**. The expected NPV for the environmental and the implementer's outcomes were negative in almost all model runs. The aggregated expected NPV for the total project was negative in virtually all model runs (**Figure 4-4a**), with projected losses ranging between $5.72 and $14.56 million. When dam construction was complemented with catchment restoration, the aggregated NPV was between a loss of $9.69 million and a gain of $340 thousand (**Figure 4-5a**).

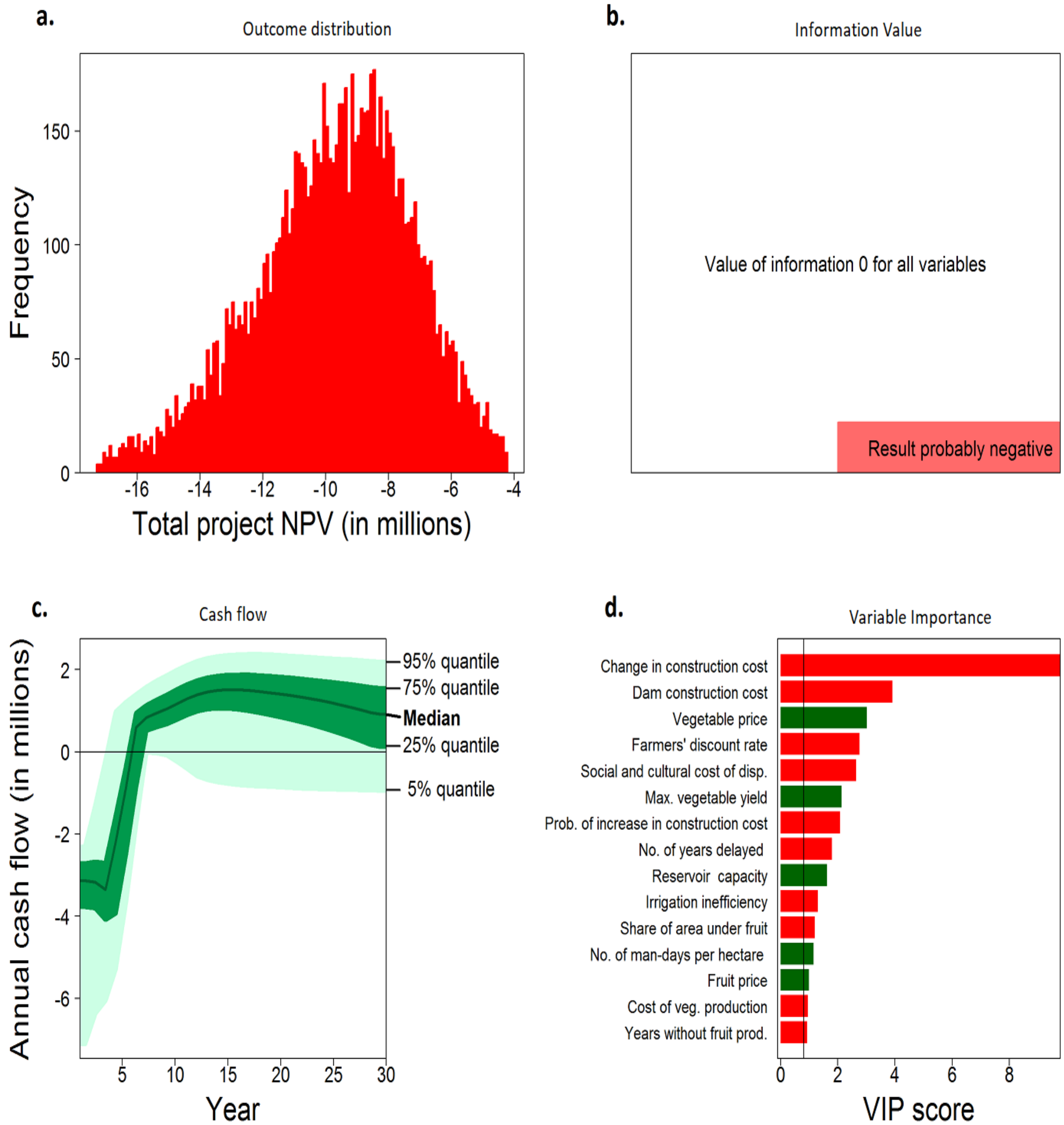

Figure 4-4: The overall project outcomes of implementing an irrigation dam without catchment restoration in Tigray.

a. *distribution of project outcome expressed as the Net Present Value (NPV), positive (green) and negative (red).* ***b.*** *Expected Value of Perfect Information (EVPI). EVPI>0 indicates that the selected uncertain variable has information value and further measurement is recommended to reduce model uncertainty.* ***c.*** *distribution of modeled annual net cash flow over the expected project life span of 30 years.* ***d.*** *variable of importance in the projection (VIP) highlighting all model variables with a VIP greater than 0.8 (black vertical line) and correlation with project outcome, positive (green) and negative (red).*

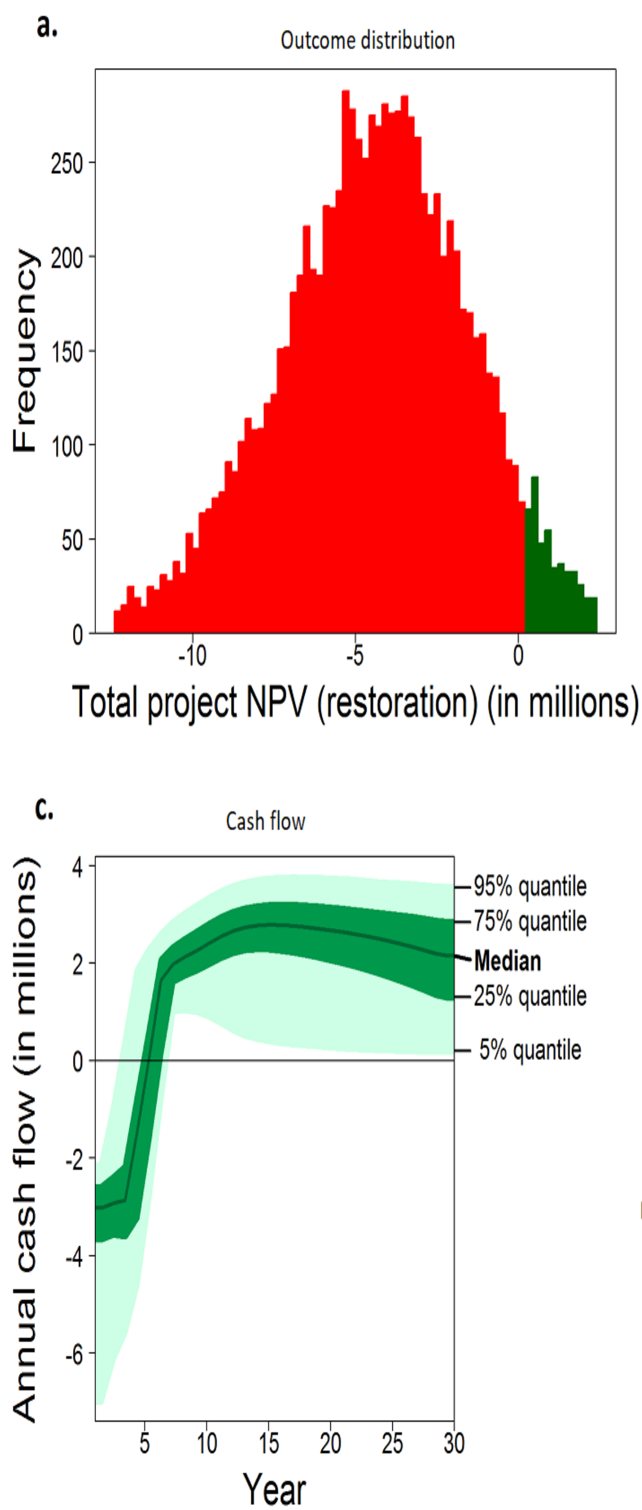

Figure 4-5: The overall project outcomes of implementing an irrigation dam with catchment restoration in Tigray

*For detailed description of the graphs and bars, see legend to **Figure 4-4***

4.3.2. Food security and nutritional outcome

The proposed irrigation dam is likely to improve local community members' overall food and nutritional status by supplying additional energy and Vitamin A (**Figure 4-6**). The additional supply of energy and Vitamin A is higher when the dam construction is complemented with catchment restoration. With catchment restoration, the food produced in the irrigation scheme could be enough to meet the annual energy needs of 19 thousand and the pro-vitamin A needs of 894 thousand people over the expected life of the project (i.e. 50^{th} percentile), with this figure slightly declining to 16 and 845 thousand people when the project is undertaken without catchment restoration.

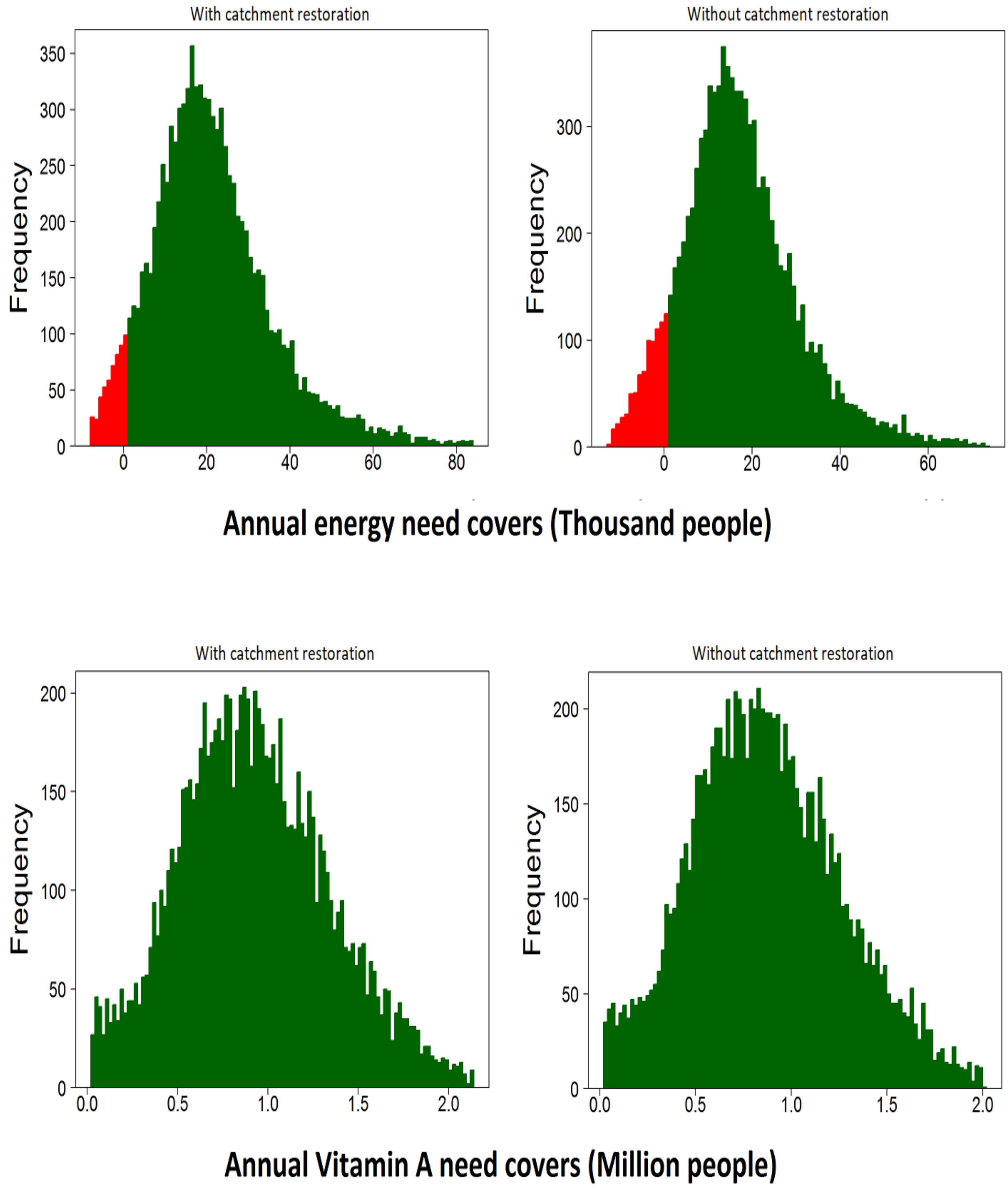

Figure 4-6: Nutritional outcome of implementing an irrigation dam in Tigray, Ethiopia

Number of additional people whose annual energy (top) and Vitamin A (bottom) needs could be covered by the additional food production enabled by a planned irrigation dam, with and without catchment restoration, in Tigray, Ethiopia.

4.3.3. Sensitive parameters

PLS regression analysis results indicate a number of variables that strongly influenced the expected net outcomes for the overall project (**Figure 4-4d**; **Figure 4-5d**) as well as for each stakeholder (e.g. **Figure 4-7d**; **Figure 4-8d**), the environment, and the implementer (see appendices: **Figure A-1d; Figure A-2d)**. VIP scores revealed that the distribution for the total project NPV was positively influenced by the *price* and *maximum attainable yield of vegetables*, the *water holding capacity of the reservoir*, the *farm employment created*, the *price of fruit*, and the *maximum irrigable area* under the scheme (**Figure 4-4d**). The *annual rate of increase in construction cost*, the *initial estimated dam construction cost*, and the *farmers' discount rate* were the most uncertain variables that were negatively associated with the total project NPV. The value of the ecosystem services obtained from the catchment restoration also affects the distribution of total project outcomes (**Figure 4-5d**).

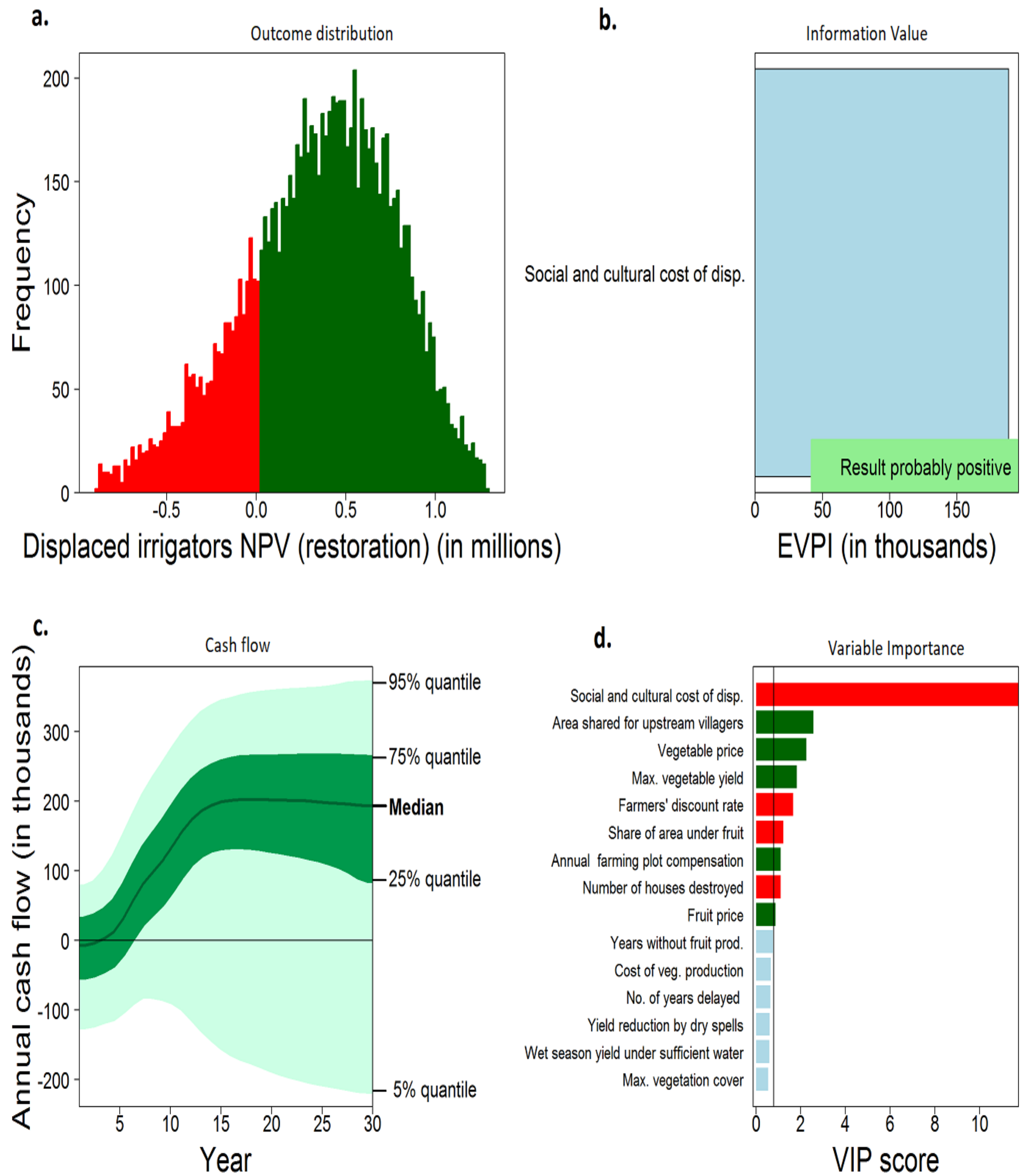

Figure 4-7: The overall project outcomes for displaced farmers

Results of 10,000 Monte Carlo model runs for farmers who are displaced and resettled with access to irrigation from the implementation of the proposed dam, with catchment restoration, in Tigray, Ethiopia. For detailed description of the graphs and bars, see legend to ***Figure 4-4****.*

4.3.4. Variables with information value

The value of information analysis revealed a high EVPI of the parameter *social and cultural cost of displacement* in the model outcome (NPV) of the displaced farmers (**Figure 4-7b**). In addition, the *yield reduction effect of a dry spell*, the *probability of dry spells*, and the *total crop area* further below the irrigation scheme had high EVPI values for downstream non-irrigators (**Figure 4-8b**). For the total project outcome, the value of information analysis indicated that no variable had non-zero EVPI (**Figure 4-4b**; **Figure 4-5b**), indicating that no further measurements are needed to evaluate the overall viability of the project.

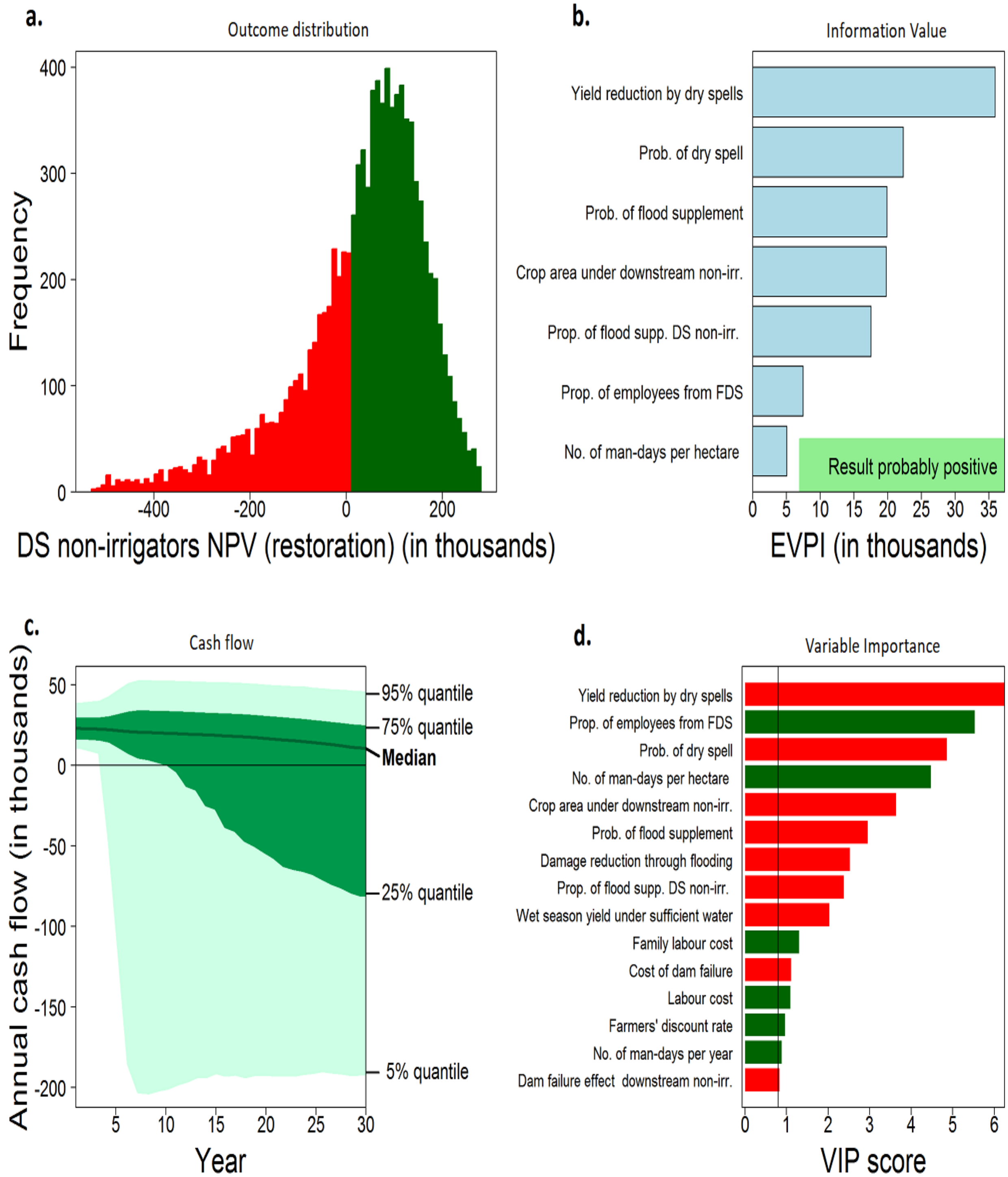

Figure 4-8: The overall project outcomes for downstream non-irrigators

*Model results from 10,000 model runs for the downstream non-irrigators of the implementation of a proposed irrigation dam project, with catchment restoration, in Tigray, Ethiopia. For detailed description of the graphs and bars, see legend to **Figure 4-4**.*

4.4. Discussion

The proposed dam construction intervention affects the composition and configuration of the landscape, which in return influences the local biodiversity, ecosystem functions, and the provisioning of ecosystem service (Bai et al., 2018). In Tigray, sedimentation is one of the main problems that influences the effectiveness of an irrigation dam (Berhane et al., 2016). Sedimentation could be strongly reduced through restoration of degraded catchment area (Alemayehu et al., 2009; Mekuria et al., 2011; Balana et al., 2012). Thus, I considered catchment restoration as a way of complementing the intervention and evaluated the outcomes with and without catchment restoration.

4.4.1. Projected outcomes of the dam intervention

In general, the proposed project is expected to have a positive NPV for all stakeholders in the community, but the high investment cost of the structure leads to negative total project outcomes. The negative project outcome could be reduced by complementing the intervention with catchment restoration, but the overall prospects remain negative even then. Thus, based on overall cost-benefit considerations, construction of an irrigation dam in the study area is not advisable. This supports results by Petheram et al. (2016) in a semi-arid tropical catchment of northern Australia, who found that construction of water storage to irrigate perennials as well as year-round cropping was prohibitively expensive and generated low return on investment. Manikowski & Strapasson (2016), also found a negative NPV for a large irrigation dam in the Senegal River Valley in Senegal.

Net benefits were greatest for downstream irrigators, followed by displaced farmers, upstream non-irrigators, and downstream non-irrigators. Farmers with access to the proposed irrigation scheme benefited most. As with past studies, the findings show that the benefits from irrigation are mostly attributed to increasing numbers of crop harvests per year and reducing crop failure during dry spells (Gebregziabher et al., 2009; Hagos et al., 2009; Mengistie & Kidane, 2016). Among farmers who do not have access to irrigation, upstream non-irrigators are expected to benefit more from the proposed project than downstream stakeholders. A major reason for this is that development of the dam may jeopardize the option of downstream non-irrigators to reduce the incidence of crop failure by diverting flash floods into their farming plots (i.e. spate irrigation), which is a common practice in the study area (Haile et al., 2013; Yazew et al., 2014a). Upstream villagers will save significant amounts of time by harvesting water from the dam for domestic and livestock consumption, because in the absence of the dam, they have to travel long distances to fetch water. In general, the use of the dam for either irrigation or domestic and livestock consumption is beneficial. The magnitude of the benefit is related to the degree of extraction (i.e. those who extract most, in this case downstream irrigators, who have the largest share of irrigable area in the scheme, stand to benefit most).

The proposed intervention is expected to lead to land use and cover changes, which in return will affect the provisioning of ecosystem services. Thus, the environmental impact of the proposed intervention is the net change in the ecosystem services. Comparing the environmental costs and benefits, the cost of the proposed dam (i.e. without catchment restoration) outweighs the benefits. This is mainly due to the loss of vegetation, such as shrubs, wetlands, and forest areas further downstream, caused by retaining water in the dam (Amdihun, 2008; Manikowski and Strapasson, 2016). The value of ecosystem services provided by area expected to become submerged is likely to outweigh additional provisioning of ecosystem services from the newly established land use system. However, when the dam construction intervention is complemented with catchment restoration, the environmental benefits exceed the costs.

The implementer may also incur losses from the proposed project, but since this implementer is the government, generating profits may not be a primary objective. However, the government might benefit from the political stability, poverty reduction, and other human development outcomes created in the area, which I did not monetize. Considering these effects, which should be highly desirable for a government serving the public interest, could improve the total project outcome.

The proposed irrigation project has the potential to improve food and nutrition security, both of which are highly associated with low agricultural productivity and dependency of smallholder farmers on rain-fed production in which small weather shocks can have significant effects (Amede et al., 2008; Hagos et al., 2012; Smajgl et al., 2016). Model results concur with other studies that access to irrigation can be key to reducing food insecurity by increasing agricultural productivity and stabilizing farming outputs in the face of climate change and weather variability (Gebregziabher et al., 2009; Hanjra et al., 2009a; Clothier et al., 2010; Namara et al., 2010; Burney and Naylor, 2012; Dile et al., 2013; Ringler et al., 2016). In this study, I considered only the additional energy and pro-vitamin A produced from the dry season irrigation together with the damage prevention during dry spells. However, households may also supplement and improve their diet using the on-farm employment income related to the dam intervention, which could in turn improve the food and nutrition outcomes of the project.

4.4.2. Sensitive variables

4.4.2.1. Variables related to the cost of construction

The construction-related variables (i.e. the *initial estimated cost of constructing the structure*, the *likelihood and rate at which construction cost increases*, and *delay in the completion of the structure*) were negatively correlated with the total project NPV. This is in line with the global assessment of large dams report by the World Commission on Dams, in which the high construction cost of large dams and additional cost overruns incurred by construction delays were mentioned as raising the likelihood of negative project outcomes (WCD 2000). Increases in a single or combination of all these variables reduce the overall project outcomes. This suggests that it may not be advisable to invest in areas where the investment cost is high and delays can easily occur.

4.4.2.2. Variables related to farm revenue

The *price and maximum yield of vegetables*, *maximum irrigable area* under the scheme, as well as the *fruit price* are positively associated with the total project outcome. This complements the result of Amede et al. (2008), and Hagos et al. (2009), who reported that the national economy is more strongly impacted by changes in the prices of irrigated vegetables and fruits than by the same changes in the price of other crops. While an increase in fruit price increases the expected NPV, the number of years until first fruit harvest and the area allocated to fruit reduces the total project outcome. This suggests that irrigation development interventions should target high-yielding vegetable farming.

4.4.2.3. Variables related to reservoir capacity and water use

Irrigation inefficiency influenced the distribution of the overall project outcome negatively. The water loss due to inefficiency varies with the irrigation technology or method used (Brouwer et al., 1989; Asres, 2016;). The proposed intervention relies on a furrow irrigation system, which is relatively inefficient. Adoption of more advanced irrigation methods could improve water use efficiency (Kifle et al., 2017), which in turn allows increasing the irrigated area. It is important, however, to ensure adequate drainage to prevent salinity build-up, as well as sufficient groundwater recharge to avoid undesirable downstream consequences. These considerations are beyond the scope of this study, but should be factored into decisions on which irrigation technique to adopt.

Reservoir capacity was positively associated with total project outcome, with an increase in this variable resulting in a greater command area, which in turn increases the irrigation revenue. The importance of this parameter is underscored by findings from a large irrigation dam at Kogo, Ethiopia, where the irrigable area was reduced by almost 20% compared to initial expectations due to a reduction in reservoir volume (Asres, 2016). Therefore, irrigation development interventions should consider the uncertainty in the reservoir's capacity and irrigation inefficiency to accurately anticipate irrigation benefits.

4.4.2.4. Variables related to employment and relocation

Irrigation practices are often labor-intensive (Gebregziabher et al., 2009), which implies that they can generate employment. The *total amount of labor created* (quantified in man-days per hectare in this study) positively influences the total project outcome. While this generates costs for the irrigators, the income generated by such employment could improve the social wellbeing of the non-farming members of the community.

Irrigation dams often lead to the displacement of farmers who previously cultivated the area that is flooded. The government already negotiated the issue of displacement, and the farmers agreed to be relocated to areas with better infrastructure. The government will pay compensation for the houses destroyed and farming plots inundated. Even though this compensation is vital to overcome some livelihood problems, loss of homes and social bonds have negative implications.

Considering such costs reduces the total project outcome. Therefore, the net benefits of an irrigation dam project could be improved by selecting an appropriate location that leads to displacement of fewer farmers.

In general, the findings of this study revealed that investment in an irrigation dam could improve household incomes, as well as food and nutrition security, albeit at the cost of environmental externalities and high investment costs. However, complementing the dam construction intervention with catchment restoration could reduce the expected project losses, because the ecosystem value obtained from catchment restoration is enough to cover some of the costs of the intervention. Thus, the dam construction intervention should be complemented with the restoration of degraded catchment areas. Moreover, the investment outcomes can be improved through reduction of water losses due to inefficiency, targeting high-value crops, and controlling construction cost overruns. Furthermore, the study revealed that the social and cultural costs to the displaced farmers and the wider impact on farmers further downstream, which are often neglected during impact assessments, should be considered in irrigation development interventions.

The study demonstrates that a decision analysis approach can help overcome some of the weaknesses of commonly used deterministic, *ex-ante* project evaluation techniques (i.e. cost-benefit analysis) by thoroughly capturing all relevant impact dimensions and their inherent uncertainties, addressing system complexity, and confronting data scarcity. The approaches demonstrated in this study can support decision making for agricultural development investments and provide guidance on resource allocation.

4.4.3. Methodological Limitation

The development of the impact pathway model was done by the experts, and there is no guarantee that all important aspects of the proposed intervention and their estimates are accurately captured (Luedeling et al., 2015). In addition, the ecosystem services obtained from the intervention are considered only for the expected life of the dam (i.e. 30 years, including construction), yet the services could be provided for more than the expected life of the dam, which might lead to positive project outcome.

CHAPTER FIVE: STOCHASTIC IMPACT EVALUATION OF ROAD-WATER HARVESTING INTERVENTION IN NORTHERN ETHIOPIA

Abstract

For efficient resource allocation and optimized returns from development interventions, decisions should be made based on detailed *ex-ante* evaluation. However, due to measurement difficulties, and a lack of appropriate tools to integrate the available uncertain information, such evaluation often remains inadequate. Stochastic Impact Evaluation (SIE) presents a novel approach for evaluating complex development projects in the face of system complexity, uncertainty and variability. We used SIE to evaluate the viability of road-water harvesting interventions in the Tigray region of Ethiopia. After eliciting expert knowledge about the planned intervention, we generated a causal impact pathway model and collected estimates for all parameters. We used SIE tools, including Monte Carlo simulation, Partial Least Squares regression and Value of Information Analysis, to forecast project outcomes, identify sensitive parameters and detect critical knowledge gaps in decision-making. The experts identified percolation ponds, farm ponds, and check dams as suitable strategies for harvesting road-water. Model results indicated that the communities in the vicinity of the road are likely to benefit from road-water harvesting structures, while such measures are costly for the implementer. Harvesting flood water using percolation structures was found likely to generate positive impact, the opposite was true for check dams. Harvesting road-water using farm ponds could generate positive impacts, but Understanding the viability of these interventions is hindered by several knowledge gaps that should be narrowed by measurements before an investment decision is taken. This case study confirms the feasibility of using the SIE approach for analyzing decisions on complex systems under uncertainty, suggesting broad applicability to similarly complex decisions.

Key words: Climate-smart Roads, Feasibility study, Decision Analysis, Simulation

5.1. Introduction

5.1.1. Background

Developing countries such as Ethiopia generally suffer from poorly developed infrastructure. To accelerate economic development, many countries have begun investing heavily in infrastructural development. Investment in roads equipped with road-water harvesting infrastructure can play an important role in reducing poverty and enhancing economic growth and development (Hatibu et al., 2006; Demenge et al., 2015), particularly in countries where large proportions of the population reside in rural areas. Access to road infrastructure enhances the adoption of agricultural technologies and access to inputs, which can increase agricultural productivity (Acheampong et al., 2018). If road-water harvesting structures are added, rainfall-dependent farmers may derive considerable benefits through increased reliability of irrigation water supply (Torres et al., 2016).

The impact of road development on poverty and economic growth is well documented (e.g. Fan and Chan-Kang, 2008; Faiz et al., 2012; Acheampong et al., 2018; Aggarwal, 2018). Roads enhance rural and urban market integration and improve access and mobility of people and goods (Demenge et al., 2015; Acheampong et al., 2018; Aggarwal, 2018). Resulting market integration and increasing farm inputs (Aggarwal, 2018) can increase agricultural productivity (Acheampong et al., 2018). For Ethiopia, Worku (2011) evaluated the macroeconomic impact of road sector development on the growth of the national economy, showing that the expansion of road networks positively influenced economic growth. However, at the micro level, people's ability to benefit from expanding road networks is largely associated with their initial asset holdings (i.e. land and livestock) and existence of effective integrated development projects (Demenge et al., 2015). Moreover, the poverty reduction effects of expanding road networks vary with the type or grade of the road (Fan and Chan-Kang, 2008; Worku, 2011).

Expansion of the road network can facilitate economic growth and development, but it can also have a detrimental effect on the landscape, hydrology, and ecology of affected areas (Forman and

Alexander, 1998; Jungerius et al., 2002; Liu et al., 2008; Patarasuk and Binford, 2012; Puertas et al., 2014; Demenge et al., 2015). For example, reduction of forest, grassland, farm, and shrub-land areas due to expansion of road networks has been observed in southwestern China (Liu et al., 2008). The construction of roads can affect permanent and seasonal river flows, and compromise the livelihoods of local populations (Jungerius et al., 2002; Puertas et al., 2014; Demenge et al., 2015).

The negative impacts of road construction can be minimized by the construction of effective water harvesting structures, which can generate additional benefits to communities in the vicinity of the roads (Demenge et al., 2015; Van Steenbergen et al., 2019). Investments in water harvesting structures can increase household income, reduce food insecurity, and promote sustainable development (Hagos et al., 2012; 2017; Zhang et al., 2018). Water harvesting technologies can significantly increase crop yield, improve factor productivity, create employment opportunities and reduce crop failure (Bouma et al., 2016; Hagos et al., 2017). The contribution of water harvesting can be particularly significant in areas where most people are reliant solely on rainwater, as is common in large parts of Sub-Saharan Africa (Hatibu et al., 2006; Molden et al., 2010; Hagos et al., 2013). Furthermore, lack of water harvesting structures (or poor construction) can cause road damage, which incurs additional costs for repair and maintenance (Demenge et al., 2015). In summary, complementing road construction with water harvesting structures promises a range of benefits.

5.1.2. Stochastic Impact Evaluation

For efficient resource allocation and to optimize returns from development interventions, decisions on such interventions should be based on detailed *ex-ante* evaluation. However, due to a paucity of precise and reliable information, measurement difficulties and lack of appropriate tools to integrate uncertain information, intervention outcome forecasts have often remained inadequate (Peterman and Anderson, 1999). Accordingly, decision-makers often evaluate development projects based on perceived economic and technical feasibilities without quantitative analysis of other outcome prospects (Luedeling et al., 2015). Solely relying on intuition is often inadequate for development decisions on complex agricultural systems, where intervention outcomes are shaped by environmental, socio-economic, and cultural factors

(Luedeling and Shepherd, 2016). Prospective impact analysis is important in such settings, because development interventions may have unintended effects on land use and land cover of the target area and jeopardize ecosystem services that local communities depend on (Bai et al., 2018). Holistic *ex-ante* appraisals that strive to capture all major impacts of interventions and adequately consider uncertainty and variability can help alleviate the risk of such undesirable consequences (Luedeling et al., 2015).

Recent case studies have demonstrated the applicability of Stochastic Impact Evaluation (SIE) as a promising technique to evaluate complex decisions that must be taken in the face of uncertainty and variability, even in data-limited environments (Luedeling et al., 2015; Wafula et al., 2018). SIE is a probabilistic decision-focused approach that supports practical decisions on agricultural development interventions in the face of system complexity, risk and imperfect information (Whitney et al., 2017; Lanzanova et al., 2019). The approach allows for the integration of different impact dimensions into impact pathway models. It also allows for the projection of plausible ranges of intervention outcomes. Despite its suitability for decisions on agricultural systems, the approach has rarely been applied to evaluate agricultural development interventions (Luedeling et al., 2015). Among the few case studies that have been examined with this methodology are a reservoir protection decision in Burkina Faso (Lanzanova et al., 2019), honey value chains in Kenya (Wafula et al., 2018), home-gardens and the future of food and nutrition security in Uganda (Whitney et al., 2017), water supply in Kenya (Luedeling et al., 2015), and irrigation development in Ethiopia (Yigzaw et al., 2019a).

Although climate-smart road infrastructure that includes water harvesting is gaining global attention for reducing flood damage and optimizing the benefits derived from harvested water (Puertas et al., 2014; Demenge et al., 2015), the economic viability of the infrastructure has not yet been assessed. Studies thus far have usually dealt separately with road construction (c.f. Browne and Ryan, 2011) and water harvesting (Bouma et al., 2013). Here we demonstrate the use of SIE techniques to evaluate the viability of road-water harvesting interventions in the Tigray region of Ethiopia. We used the participatory methods and computational tools of SIE to predict the plausible outcomes of investing in road-water harvesting interventions, identify critical uncertainties that influence the intervention decision, and evaluate whether outcome projections based on the current state of knowledge are adequate for supporting road-water harvesting decisions.

5.2. Methods and Materials

5.2.1. Location

We conducted this study in the Tigray region of northern Ethiopia. The region has a semi-arid climate, with annual rainfall between 450 and 980 mm, mainly falling during the summer season. More than four fifths (83%) of the population in the region are reliant on rain-fed agriculture (Government of Tigray, n.d.). The incidence of poverty in Tigray is higher than elsewhere in Ethiopia. According to the 2015/16 *Ethiopian Welfare Monitoring* survey report, nearly one in three people in Tigray were living below the food poverty threshold of 2200 kilocalories per day, which is considered the minimum energy requirement for healthy work (National Planning Commission of Ethiopia, 2017).

The road density in Ethiopia is very low, especially in Tigray, which features only about 6200 km of roads on a total area of 50,079 km^2 (**Figure 5-1**). The regional government, in collaboration with the federal government and other development partners, has been working to expand the road network. The region is endowed with many seasonal and annual streams, which cover a length of 20,571 km (see **Figure 5-1**) and may be affected by the planned road network expansion. If adequate structures are put in place during road construction to enable collection and productive use of stream and road runoff water, road construction may produce considerable co-benefits for local agricultural communities.

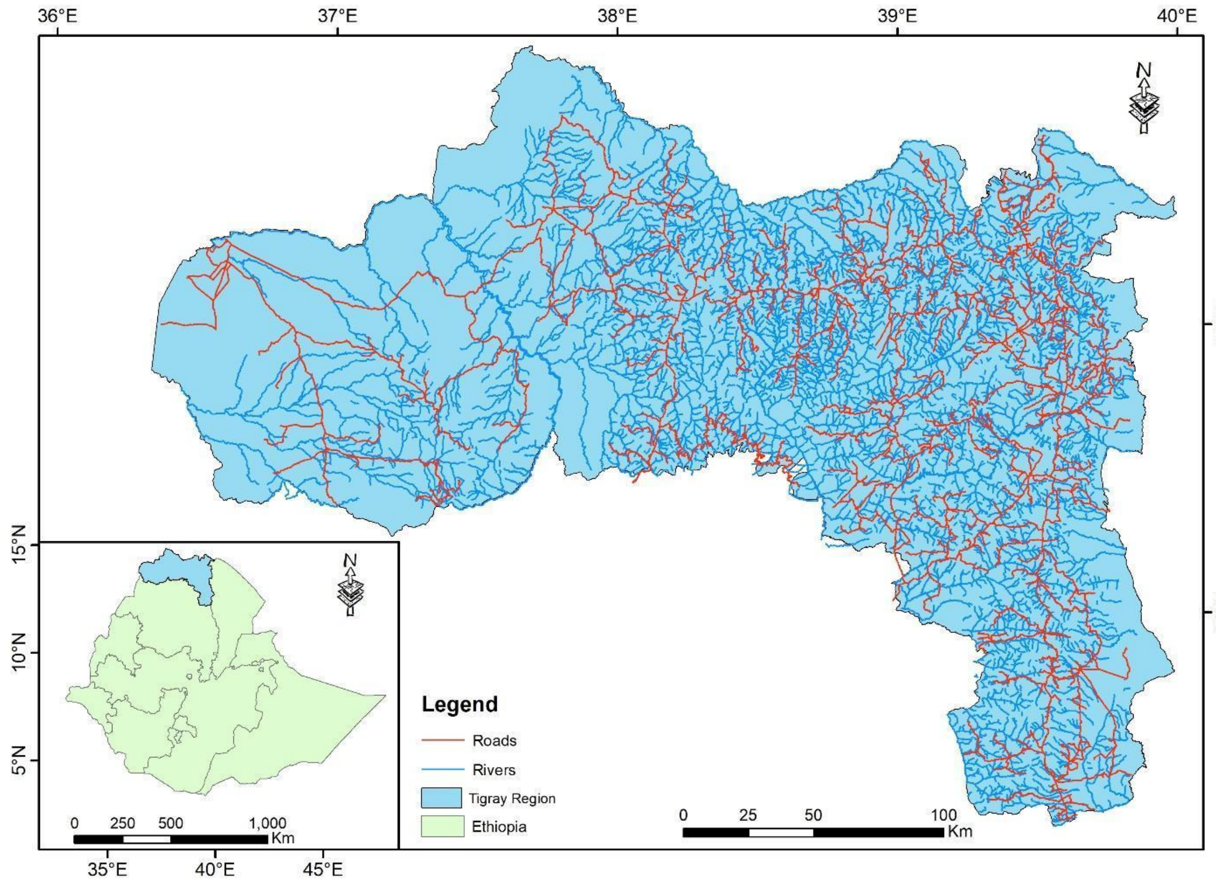

Figure 5-1: Map of Tigray Region with its perennial and seasonal streams and the road network

5.2.2. Model Development and Parametrization

5.2.2.1. Modeling Approach

I developed an impact pathway model using all available sources of information including expert knowledge. Expert knowledge is often the best available source of information in complex systems where little data is available (Hadorn et al., 2014; Morgan, 2014; O'Leary et al., 2015).

We held a four-day model development workshop about road-water harvesting interventions in Wukro, Ethiopia. The workshop included 14 experts, five from the region's Water Resource Bureau, three from the Agricultural and Rural Development Bureau, three from the Ethiopian Roads Authority, Adigrat district office, and three from Wukro Agricultural College (3). These experts were identified based on their exposure to road construction and water harvesting interventions.

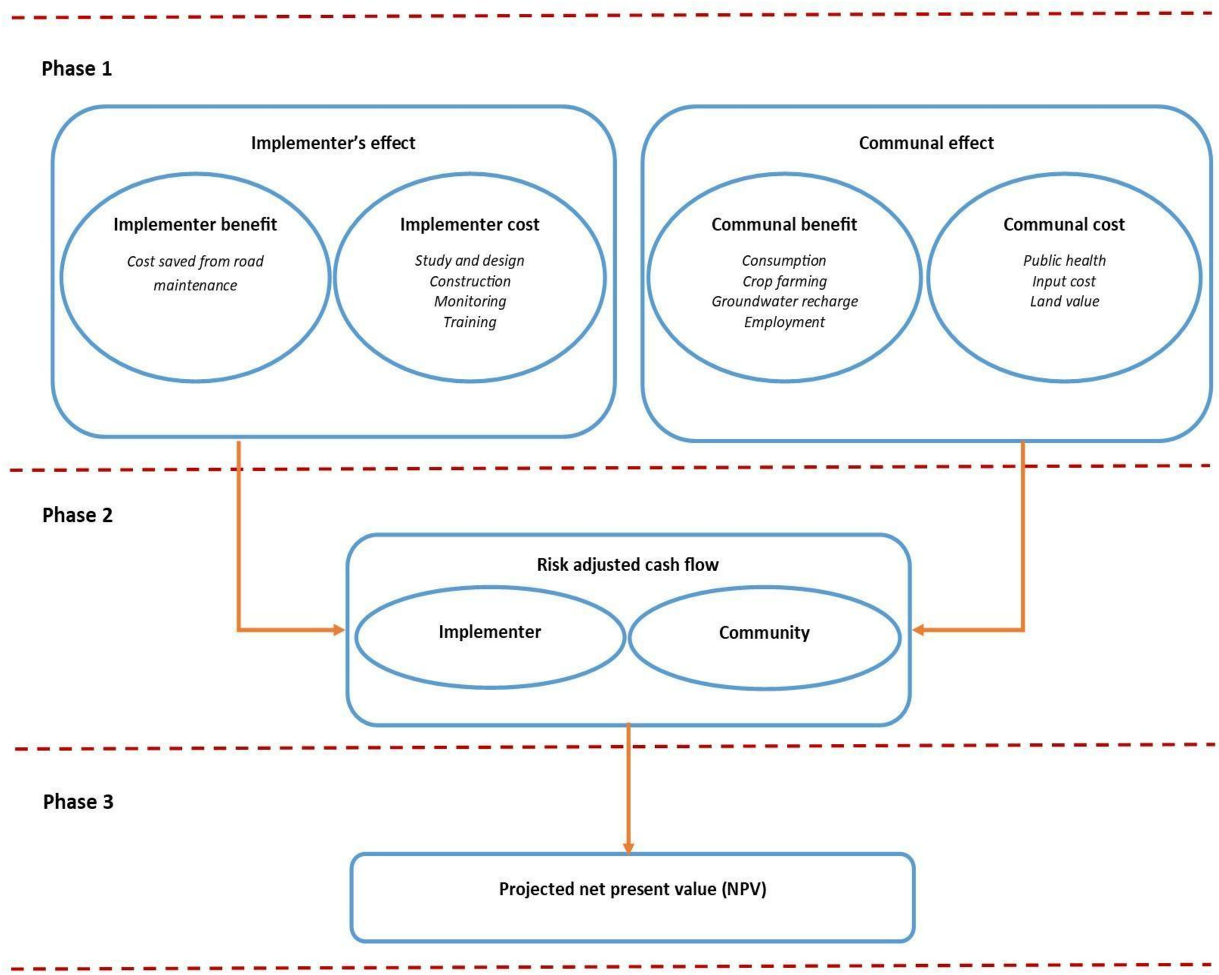

Figure 5-2: Conceptual illustration of an impact pathway model for road-water harvesting interventions in northern Ethiopia

We designed the workshop to ensure the active participation of all experts. To facilitate brainstorming and development of an impact pathway model, we asked experts to 1) identify types of road-water harvesting structures that might be worthy of investment by the government in order to improve societal welfare, and 2) identify the costs, benefits and risks involved in road-water harvesting with each of the identified interventions. Experts were asked to find answers to a set of intervention-specific questions. They were split into three groups and asked to first consider each intervention-specific question individually and then to refine their ideas through discussion with the other experts in their groups. Results from each group were presented, discussed, and consolidated in plenary sessions. This procedure was repeated for each identified road-water harvesting intervention. The impact pathway model for the road-water harvesting intervention was then consolidated from these results and subsequently reviewed by all experts. The experts thus identified all the plausible costs and benefits of road-water harvesting interventions (**Figure 5-2**: Phase 1). Together we framed the final impact pathway model (**Figure 5-2**), including all the relevant costs, benefits, and risks of road-water harvesting interventions.

Three types of road-water harvesting structures were identified by the experts as promising and worthy of consideration in this study, i.e. they were considered potentially viable investments for harvesting road-water to increase societal welfare. These structures are percolation ponds, farm ponds and check-dams, which can be constructed independently or jointly. We modeled the impact pathway for each of these interventions and evaluated their viability both independently and jointly.

- ***Percolation ponds:*** this structure is expected to harvest rain or flood waters that drain onto roads. The purpose of this structure is groundwater recharge to enhance available water resources at the catchment level. Since the objective of building such a structure is recharging the groundwater, it does not need to be blanketed or cemented and it can be filled up to five times in a single year.
- ***Farm ponds:*** this structure is an *in-situ* water harvesting structure that can be constructed to support individual farm households. The water that is stored in this structure can have three main benefits: home and livestock consumption, supplementing rainfed cropping systems during dry spells and providing irrigation during the dry season.
- ***Check-dam:*** this structure is constructed in eroded gullies to store water that flows from streams and intermittent rivers. It can provide water for home and livestock consumption, irrigate nearby farms, and recharge the groundwater.

In *Phase 2* (**Figure 5-2**), the model was converted into mathematical equations to estimate the risk-adjusted cash flows for the implementer and the communities, as well as anticipate overall impacts. The projected cash flows were then discounted to derive the net present value of constructing the road-water harvesting structures (*Phase 3*). The overall economic impact of road-water harvesting interventions was considered to be the difference between the additional cost of constructing water harvesting structures and the additional expected return from having the structures.

The model was designed to estimate the value per one kilometer of road construction, for comparability to other studies that use 1 km as the unit of analysis (e.g. Jungerius et al., 2002). Monetary values were collected in the Ethiopian currency (Ethiopian Birr; ETB) and converted into US dollars (using an exchange rate of 27 ETB USD^{-1}).

We relied on expert knowledge for estimations of input values for the model. We trained the experts through a process known as 'calibration training' in order to elicit reliable estimates (i.e. assessments of the experts' state of uncertainty) and to overcome individual biases (i.e. over or under confidence) (Hubbard, 2014). We consolidated the experts' estimates to express the collective 90% confidence intervals (i.e. the experts are 90% certain that the actual values lay within the estimated value ranges). The estimates were specified by lower (5%) and upper bounds (95%) of the confidence intervals, as well as the shape of the expected probability distribution. See the input table for the estimates for each parameter (see appendices **Table A-4**).

5.2.2.2. Simulation

The final model was transcribed into a set of mathematical equations to simulate the impact of the road-water harvesting interventions. The code of the impact pathway model was written in the R programming language (R Core Team, 2022). All code and data are included in a repository (https://github.com/CWWhitney/21_Ethiopia_Roadwater_Harvesting). The simulation result, which is described as Net Present Value (NPV, is the difference between the sum of all discounted benefits and costs after considering the risks.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

where *NPV* is the net present value; *n* is total simulation period; R_t is the net cash flow at time *t* (cash inflow minus cash outflow at a time *t*); and *i* is the discount rate.

I ran the simulation using the 'decisionSupport' package (Luedeling et al., 2022). We used the model to simulate the plausible intervention outcomes, expressed as Net Present Value (NPV). The project outcome was computed by discounting the forecasted net cash flows (i.e. the difference between risk-adjusted costs and benefits) of the proposed interventions. I ran the model 10,000 times as a Monte Carlo simulation. For each run of the model, the algorithm selects a random value from the predefined estimates and distributions of the input parameters and uses these to produce a single project outcome (Rodríguez, 2013; Rosenstock et al., 2014). The overall population of outcomes across all runs of the Monte Carlo simulation expresses the expected outcome distribution for the intervention. We present the simulated outcomes as percentiles.

5.2.2.3. Sensitivity Analysis

Uncertain parameters have varying levels of influence on model outcome distributions. We identify the most influential uncertain parameters that influence the outcome based on the Variable of Importance in the Projection (VIP) score of a Partial Least Squares regression (Wold et al., 2001; Luedeling and Gassner, 2012). The VIP shows the predictive power of the input parameters with respect to the project outcome (Wold et al., 2001). We used a VIP score value of 0.8 as cutoff threshold for variable selection (i.e. variables with a score of 0.8 and above were considered influential). This threshold has frequently been used in comparable studies (e.g. Lanzanova et al., 2019; Yigzaw et al., 2019; Ruett et al., 2020).

5.2.2.4. Critical knowledge gaps

In many cases, simulation results using the initial estimates are capable of generating enough information to guide decision-makers. However, sometimes the emerging picture remains unclear, so that decision-makers find themselves unable to make confident and informed decisions. In such a situation, a Value of Information (VoI) analysis can indicate where conducting further measurements could improve the decision recommendation. The VoI analysis identifies those uncertain parameters for which further measurement would be helpful in terms of facilitating the decision-making process (this is the case for all parameters with information values greater than zero). We calculated the VoI, expressed as the Expected Value of Perfect

Information (EVPI) (Luedeling et al., 2015), to show the difference between the expected value of a decision outcome with perfect information on a particular model variable (i.e. after integrating additional information) and the expected value of a decision outcome with imperfect information (Boncompte, 2018; Lanzanova et al., 2019). VoI calculations can prevent decision-makers from making a poor decision. It does this by pointing them to critical knowledge gaps that should be narrowed before the decision is taken (Oostenbrink et al., 2008; Wafula et al., 2018). The EVPI shows a positive value for all the critical uncertain parameters for which further measurement might add value to the decision-making process. The EVPI can be thought of as the amount of money that a decision-maker should be willing to invest in order to learn more about uncertain parameters.

5.3. Results

5.3.1. Decision Modeling

The impact pathway model (**Figure 5-2**) offers a coarse overview of the main factors that are important regarding road-water harvesting interventions in the Tigray region of Ethiopia. The impact pathway model comprises all the plausible costs, benefits and risks of a road-water harvesting intervention in Tigray (**Figure 5-2**). Accordingly, the proposed intervention has an impact on the implementer (i.e., the agency constructing the structure), and on the community (i.e., people who are impacted directly by the intervention). The project incurs both costs and benefits for the implementer as well as for the communities. The implementer is expected to benefit from not spending resources on maintaining damaged roads or constructing alternative roads (detours) during floods. The communities stand to benefit from the water stored in the road-water harvesting structures as well as from employment opportunities.

5.3.1.1. Benefits of road-water harvesting interventions

The experts identified all the parameters that derive the plausible benefits of road-water harvesting intervention as well as quantitatively estimated the magnitude of the parameters based on 90% degree of certainty. The benefits and costs of the proposed interventions are compared with a baseline scenario consisting of the current practice of constructing roads without installing water harvesting structures. The benefit of having road-water harvesting intervention is highly related to the total volume of water that can be harvested within the specified catchment area. The experts identified six benefits (see below for details). The benefits can be categorized into three categories of benefits: (i) the gains from the harvested floodwater, measured in terms of additional agricultural production (i.e. both from irrigation and from supplementing the rainfed system), provision of water for domestic and livestock consumption, and groundwater recharge; (ii) reduction of flood damage to settlements, farming plots, roads and other assets, as well as prevention of gully formation through erosion; and (iii) additional employment opportunities from farming and construction of the structures. The proposed road-water harvesting interventions are expected to generate several benefits:

- **Water for livestock and domestic consumption:** This benefit is generated by the water harvested and stored in check dams and farm ponds. This benefit is not considered for percolation ponds, which are primarily used for ground water recharge purposes only (using the stored groundwater for such purposes is possible, but its exploitation requires additional efforts). To evaluate this benefit, the total water demand for domestic and livestock consumption was initially determined and valued based on the estimated value of water (water tariff).

- **Enhanced agricultural productivity:** This benefit arises because road-water harvesting structures can 1) reduce crop losses due to dry spells during the rainy season and 2) enable irrigated agriculture during the dry season. Evaluation of this benefit first required estimates of the probability of dry spells. Whenever the impact simulation indicates occurrence of a dry spell, the harvested water is used to reduce crop losses. Otherwise, the harvested water is used for dry-season irrigation. Surplus water that is left over after compensating for the impact of dry spells is also used for irrigation during the dry season. The volume of water required for supplementing the crops during dry spells as well as for dry season irrigation was estimated by the experts.

- **Groundwater recharge:** This benefit mainly arises for percolation structures. Since check dams and farm ponds are usually blanketed with cement or compacted soil, the infiltration rate in such structures was considered negligible. Groundwater recharge was valued at an estimated water tariff of 5 to 10 Birr/m^3 of water.

- **Employment income:** The integration of water harvesting structures with road construction is expected to create employment. Labor will be needed for the construction of the structures, for repair and maintenance, in farming, and for other land reclamation practices. The total employment income from construction of the structures is estimated as a percentage of the total construction cost. For farming, income is computed as a percentage of the farming cost.

- **Flood damage reduction:** Without effective water harvesting structures installed in the intervention area, there is a possibility of flooding. This flooding may damage farmlands, settlements, roads, and other open places, and it may wash away assets. The benefit obtained from flood damage is therefore correlated with the probability of flooding. Accordingly, the flood prevention benefits were only computed for years that featured a reduction of flood damage; in other years it was valued at zero. In anticipating flood damage, we distinguished between different assets (farmland, settlement and roads) and computed asset-specific probabilities.

- **Cost savings in repair and maintenance of the roads:** Flood events can cause damage to roads, so they raise government expenses for repair and maintenance. By harvesting the water that drains into roads, flood damage can be reduced, leading to cost savings in repair and maintenance.

5.3.1.2. Costs of road-water harvesting interventions

The experts also identified costs incurred by the proposed intervention (See details below). Road-water harvesting interventions require investment in the construction of water storage and water drainage structures. The construction of water harvesting structures (including the cost for study and design as well as monitoring and supervision), and road-water drainage structures are identified as the main project costs. Moreover, communal costs are also incurred for public health protection measures (i.e. mosquito nets), farming practices (i.e. agricultural input cost), and repair and maintenance of the structures. The value foregone by converting the farming plot into farm pond is also considered.

The experts identified ten costs of road-water harvesting interventions. These costs are borne by the implementer who constructs the structure and by the communities in the vicinity of the road, i.e. the intended beneficiaries of the interventions. Since the focus of our analysis were the road water harvesting interventions, we only consider the additional costs that are incurred by integrating the road water harvesting structures. Road construction costs were not considered.

- **Implementer's costs:** These costs are borne by the implementer for the installation of the different type of road-water harvesting structures. The following types of costs are borne by the implementer:

- **Construction costs:** The implementer must cover the construction costs of the water harvesting structures. The experts estimated the cost of individual structures, which was found to be closely correlated with their expected water holding capacity. To determine the total number of structures, the expected harvestable volume of water was divided by the water holding capacity of each structure. The total cost was then computes as the product of the number of structures and the construction cost of a single structure (**Table 5-1**).

Table 5-1: Capacity and construction cost of road-water harvesting structures

Type of structure	Water holding capacity of a single structure (m^3)	Construction cost of a single structure (ETB)
Farm pond	400 – 500	8,000 –10,000
Percolation pond	400 – 500	10,000 – 15,000
Check-dams	750 –1000	40,000 – 70,000

- **Study and design costs:** Before a road water harvesting structure can be built, a suitable location for it needs to be identified. The implementer is expected to pay for site selection and feasibility studies, and for the development of a site-appropriate design. This cost category is considered as a one-time payment, with no follow-up expenses throughout the simulation period.
- **Monitoring and supervision costs:** These are costs paid for the experts who monitor and supervise the construction of the structures. The experts expressed these costs as a percentage of the cost of constructing the structure.
- **Training and awareness costs:** These costs are expenditures incurred in training the communities on how to make effective use of the water that is harvested from roads. This cost is incurred to mobilize the communities and conduct consultation meetings.

- **Costs of constructing the drainage structure:** These costs are incurred for constructing structures that drain or channel the water from the roads into the storage structures (i.e. farm ponds and check dams).
- **Repair and maintenance costs:** These costs arise for maintenance of partially damaged structures. The repair and maintenance costs of farm ponds are expected to be covered by the owner. However, check dams and percolation structures are constructed on communal lands, where contributions from local communities were considered unlikely. Thus, the repair and maintenance costs of check dams and percolation ponds are considered implementer costs, while those of farm ponds are considered communal costs.

- **Communal costs:** These costs are the costs paid or covered by the community. Here, communal costs are an aggregated cost over all individual members who are expected to benefit from the construction of road-water harvesting structures. The following costs are borne by the communities:

- **Cost of public health protection measures:** When water harvesting structures are installed in the vicinity, communities should take some precautionary measures, such as purchasing mosquito nets, water filtration equipment and medicine, to protect themselves from malaria and other water-borne diseases. These costs are considered for farm ponds and check dams, which hold water for longer periods of time than percolation ponds and are often located in the close proximity of residential areas.
- **Repair and maintenance:** As mentioned in the implementer cost section, owners of farm ponds, which are usually privately owned, are expected to cover the costs of repairing and maintaining the structures.
- **Agricultural input costs:** These are costs incurred in the agricultural production system. This cost category is most relevant for dry-season irrigation. However, during dry spells the additional cost of labour used to channel water from the structure was also considered.

- **The value of the land under farm ponds:** farm ponds are expected to be constructed on farmland, which could alternatively also be used for farming. Therefore, the value forgone by converting farming plots into farm ponds was considered as a cost.

5.3.1.3. Risks of road-water harvesting interventions

The experts identified all relevant natural and anthropogenic risks of the proposed intervention (**Table 5-2**), listing seven types of risks. Based on their expected impacts, these risks are categorized into three groups: risks that lead to total structure failure, risks that increase costs, and risks that reduce benefits. Uncertainties resulting from knowledge limitations were explicitly captured through the estimation process (i.e. the intervals between the lower and upper bounds are wide for parameters that are highly uncertain).

Table 5-2: Types of risks that affect the road water harvesting interventions

Types of risks	Expected impact of the risk on the respective structures			Remark
	Farm pond	Percolation pond	Check-dam	
Risk of total structural failure	No activity if the structure fails	No activity if the structure fails	No activity if the structure fails	All costs and benefits are zero, if the structure fails).
Risk of structural and hydraulic damage that require repair and maintenance	Increase in cost; the cost is to be borne by the farmer	Increase in cost, the cost is to be borne by the implementer		Percolation ponds and check-dams are constructed on communal land, so the implementer will cover the repair & maintenance costs.
Risk of waterlogging	Increase in cost			Cost for land reclamation. This cost is mostly incurred for wages.
Siltation risk	Reduced volume of harvestable water and flood control benefit			As the structure fills with sediments, the harvestable volume of water is reduced.
Risk to human health from infestation by malaria and other water-borne diseases	Increase in medication costs	Not applicable	Increase in medication costs	This risk affects only users of farm ponds and check dams.
Risk of water pollution from fuel spills and excavation of heavy metals	Increase in cost from pollution	Increase in cost from land reclamation from the heavy metals	Increase in cost from pollution	Fuel spills from the roads may affect the quality of harvested water. Heavy metal excavation is highly possible at catchment level, because of the slope.
Risk of low rainfall	Reduced benefits due to low water availability	Reduced benefits due to low water availability	Reduced benefits due to low water availability	Not applicable

5.3.2. Simulation results

5.3.2.1. Projected intervention outcomes

The output of the Monte Carlo simulation shows widely varying NPV projections across the three types of road-water harvesting structures (**Table 5-3**). Based on individual evaluation of the three structure types, harvesting flood water using either percolation ponds or farm ponds appeared likely to a generate positive NPV, whereas the projected NPV was found highly likely to be negative for check dams. Investing only in percolation structures is likely to generate the highest NPV per kilometer, with a value between \$18,000 and \$120,000 (i.e. 5th and 95th percentile), whereas check dams are expected to lead to a loss of between \$52,000 and \$130,000. Harvesting the expected runoff by constructing a combination of these structures is likely to generate negative outcomes, with NPV between a loss of \$44,000 and gain of \$23,000. The community in the vicinity of the road is likely to be better off with effective road-water harvesting structures, though the magnitude of benefits varies considerably between the structure types.

Table 5-3: Distribution of outcomes for the different road-water harvesting intervention

Alternative interventions	Percentile distribution of outcomes (US \$)			Mean	Chance of loss (%)
	5th percentile	50th percentile	95th percentile		
Farm pond	-28,000	2,800	31,000	2,900	42.1
Check dam	-130,000	-78,000	-52,000	-76,000	99.9
Percolation pond	18,000	78,000	120,000	76,000	1.3
Combined	-44,000	-400	23,000	-2,800	51.2

Distribution of outcomes from a 10,000-run Monte Carlo simulation for all the different road-water harvesting structures. The outcome is a Net Present Value (NPV) from harvesting water from 1 km road over a period of 10 years.

5.3.2.2. Sensitive parameters

The results of the PLS analysis provide an indication of the most informative variables that influence the project outcome. The total project outcome for harvesting water using check dams was negatively influenced by the *cost of constructing the structure*, the *harvestable volume of water in a kilometer distance*, *water usage for irrigation purposes* and the *percentage of water lost from the structure*, whereas it was positively correlated with the *water holding capacity of the structure* (**Figure 5-3**). The outcome for harvesting the water that drains onto roads using percolation structures is positively influenced by the *total harvestable volume of water in a kilometer distance*, the *filling frequency of the structure per rainy season*, and the *value of the water* that infiltrates into the ground. The projected outcome for farm ponds is positively influenced by the *irrigation revenue* and *water holding capacity of the pond*, while it is negatively influenced by the *harvestable volume of water in a kilometer distance*, *water lost from the structure*, the *risk of total structural failure*, and the *discount rate***.**

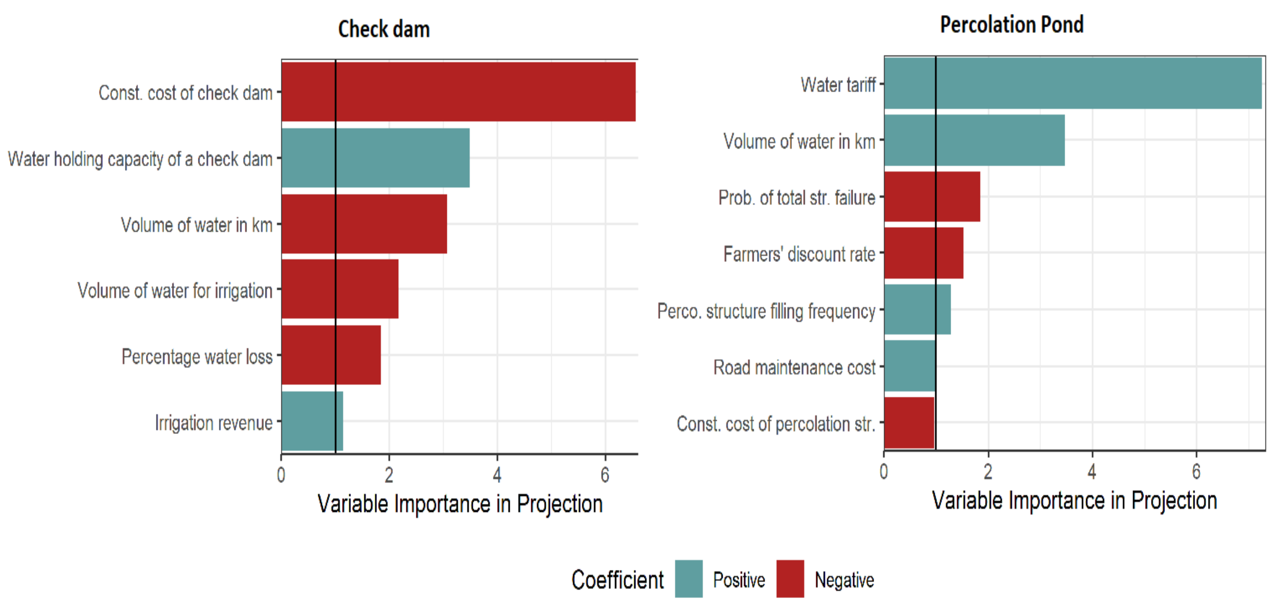

Figure 5-3: Sensitive parameters that affect road-water harvesting outcome

Sensitive parameters that affect the outcome distribution for harvesting road-water using check dams and percolation pond, as indicated by the Variable Importance in the Projection score of a Partial Least Squares regression.

5.3.2.3. Decision recommendations

The value of information analysis returned EVPI values of zero for all input variables for the models on harvesting road-water using check dams and percolation ponds (**Figure 5-4**), indicating that the current state of knowledge is sufficient for generating confident decision recommendations. Accordingly, based on the simulated outcome (i.e. the NPV), harvesting road-water using only percolation structures is recommended, whereas the use of check dams does not appear to be viable. Both conclusions can confidently be drawn, without requiring further measurements. Model simulation results for harvesting road-water indicated a high EVPI for the *volume of water allocated for irrigation purposes*, *loss of water from the structure as evaporation and seepage*, the *farm level revenue from additional water* and the *water holding capacity of the farm pond* (**Figure 5-4**). High-value variables in the simulations of harvesting road-water using a combination of all the structures included the *construction cost of check dams*, the *volume of water allocated for irrigation purposes*, the *value of a cubic meter of water* and the *loss of water from the structure as evaporation and seepage* (**Figure 5-4**). Further measurement of these variables may change the emerging decision recommendation in comparison with the initial model runs. This uncertainty should be reduced before forwarding the final recommendation (**Figure 5-4**).

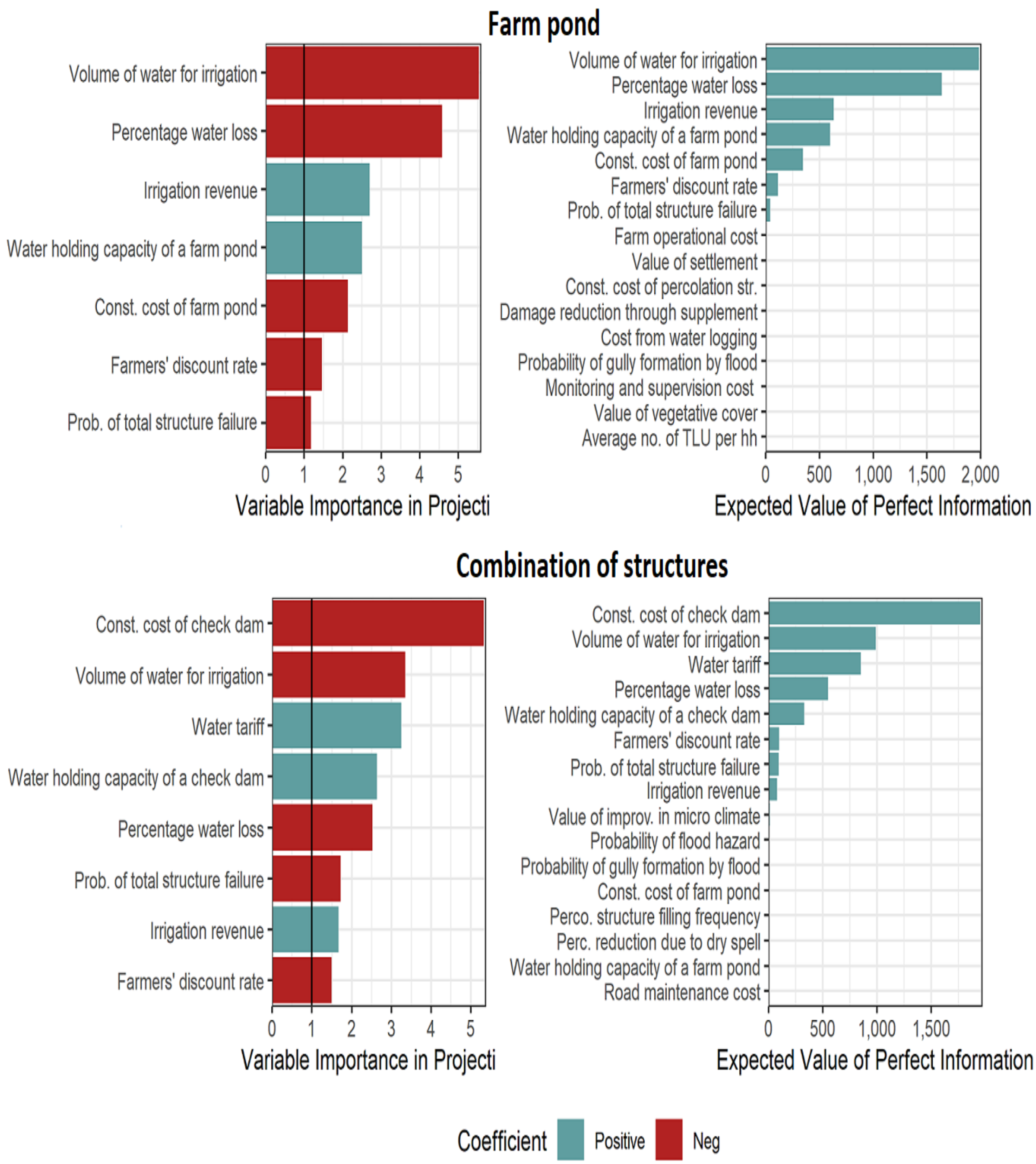

Figure 5-4: Sensitive parameters and parameters that needs further measurement (EVPI>0)

Sensitive parameters that influence the outcome distribution for harvesting road-water using farm ponds (top left) as well as the Combination of structures (bottom left), as indicated by the Variable Importance Score of a Partial Least Squares regression, and critical uncertainties according to EVPI analysis for each parameter for farm ponds (top right) and a combination of structures (bottom right).

5.4. Discussion

Ethiopia has been heavily investing in the construction of road networks and water harvesting structures to promote economic growth. Both investments enhance the productivity of smallholder farmers by allowing them to access input markets, facilitating market integration (Acheampong et al., 2018) and increasing cropping frequency as well as agricultural productivity (Berhane et al., 2016; Bouma et al., 2016). The construction of roads affects the hydrological setting of the area as well as the communities who reside in the vicinity of the roads. The rain water that is channeled into the roads leads to the erosion of farmland, it can damage the structure of the roads, and it can flood farm plots as well as homesteads. This damage can be reduced by integrating road construction with water harvesting structures, which enhance the benefits from both interventions. Both interventions can be implemented as combined structures, which have been labeled "*multifunctional roads*" (Demenge et al., 2015) or "*green roads*" (Van Steenbergen et al., 2019).

Our model results suggest that investments in road-water harvesting structures can play a role in creating resilient societies. The water that drains into or from the roads can be turned into water for domestic and livestock consumption, enhance agricultural productivity, recharge groundwater, create employment opportunities, reduce flood damage, and save costs for road repair and maintenance. However, the benefits from road-water harvesting structures vary with structure type. Hence, the viability of integrating the different water harvesting structures with road network expansion varies between the structure types. Such integration may greatly increase the benefits that are produced by rural road construction projects.

Based on our assessment, the communities who have access to the harvested water are likely to be better off when new roads are equipped with water harvesting interventions, whereas such structures incur additional costs for the implementer. In developing countries, investment in water harvesting interventions can usually only be made by the government or other development agencies, which implement such projects to strengthen food security as well as create resilient societies (Hagos et al., 2013). Since the bulk of the investment cost is borne by the implementer, the benefitting communities only need to cover the operating costs, so they are likely to derive net benefits from harvesting road-water. Therefore, integrating the expansion of roads with effective water harvesting structures can improve household income and support local climate resilience.

5.4.1. Sensitive parameters

The construction cost of the structure was identified as the most influential parameter in the outcome simulations. This is consistent with other studies in which the construction cost of water harvesting structures was found to be the most important parameter for the projected outcome (e.g. Petheram et al., 2016; Yigzaw et al., 2019). A study by Yigzaw et al. (2019) on the construction of an irrigation dam in Tigray found that the simulated project outcome (i.e. NPV) was strongly influenced by the construction cost of the structure and potential increases in the cost of construction materials. Petheram et al. (2016) also found the construction of water harvesting structures for irrigation purposes in semi-arid parts of Australia to be infeasible due to high construction costs. Therefore, controlling the costs of constructing water harvesting structure is important to ensure net benefits from the interventions.

According to our results, the actual volume of harvestable water affects the simulated project outcome (NPV) in different ways, depending on the structure type. It negatively influences the outcome for harvesting water using check dams, while it had a positive effect on percolation structures. This difference arises because the total number of structures constructed is determined by the total harvestable volume of water. The high cost of constructing check dams is the most significant parameter that influences the viability, with an increase in the number of check dams leading to higher net losses. In comparison, the construction cost of a percolation structure is relatively low, and an increase in the number of structures leads to higher net benefit. Accordingly, the simulated NPV for percolation structures is positively correlated with the total harvestable water, indicating that additional harvestable water is likely to increase the return from the additional investment. For check dams, in contrast, an additional investment in check dams, which is due to an excessive volume of harvestable water, is likely to generate negative returns. Moreover, the *water holding capacity of a check dam* is positively correlated with simulated outcomes, since larger check dams can harvest larger volumes of water, which in turn reduces the number of structures that need to be constructed. This finding supports results by Yigzaw et al. (2019), who found that the reservoir capacity of an irrigation dam positively influenced the simulated outcome. Thus, cost-efficient water harvesting structures should be integrated with road construction to increase the expected benefits.

The percentage of water that is lost through seepage or evaporation and due to inefficiencies was shown to have a strong effect on projected outcomes. This indicates that efforts to minimize losses and raise the efficiency of collection and storage structures may increase the economic value of road-water harvesting infrastructure. For example, structures that are either constructed from cement or well blanketed by compacting the soil allow little seepage, so they are effective at holding water that can be put to productive use, e.g. for dry-season irrigation. Furthermore, inefficient water use reduces the land area that can be irrigated, which in turn reduces the total expected farm revenue. Efficient application of irrigation water is thus an important means to raise net benefits from the interventions.

5.4.2. Decision recommendation

The harvesting of road-water using farm ponds has only a 58 % (**Table 5-3**) chance of generating a positive NPV, an expectation that does not allow a confident decision recommendation. Clarity of action may be raised by further measurements on the volume of water used to irrigate the area, the percentage of water lost as seepage, evaporation and inefficiency of the harvested water, the water holding capacity of the structure, construction cost of the structure and the expected revenue per hectare of land. Similarly, harvesting runoff water that drains onto and from roads using the combination of all the identified structures has a high likelihood of generating a negative outcome (51.2%), leaving a similar level of uncertainty about the preferable course of action. Greater clarity could be gained by collecting additional information about the costs of constructing check dams and the water holding capacity of such structures. The volume of water that is used for irrigation purposes, the value of the water that percolates into the ground and the percentage of water that is lost from the structures are also worthy of decision-supporting measurement.

In general, future expansion of road networks in Tigray will likely have both positive and negative implications. The positive impact of roads is widely recognized and well documented. The negative effect of road construction, especially in terms of adverse hydrological impacts, has only recently gained attention. Communities as well as household assets in the vicinity of roads can be severely affected by the floodwater that drains from roads. However, with the so-called "*multifunctional approach*" (Demenge et al., 2015), i.e. the combination of road construction with well-designed water capture structures, these negative impacts can be minimized. Harvesting the road-water that drains into or from the roads with adequate structures is therefore an interesting strategy to create climate-smart or '*green'* roads (Van Steenbergen et al., 2019) that benefit the communities. However, the structure should be designed based on the prospective return from the proposed investment. According to our analysis, harvesting road-water by constructing percolation structures is thus recommendable, whereas the use of check dams seems unlikely to be a profitable investment. Whether net benefits arise from the implementation of farm ponds or a combination of all structure types remains unclear. Additional data collection is necessary to come to clear conclusions on these interventions.

CHAPTER SIX: SOCIAL AND ENVIRONMENTAL IMPACTS OF SPATE IRRIGATION INTERVENTIONS IN TURKANA COUNTY OF KENYA

Abstract

Spate irrigation (SI) is a promising and suitable water management alternative to improve the livelihood of marginalized and resource poor dryland communities. However, its success depends on the volume of floodwater harvested, which is unpredictable both in timing, frequency, and volume. Hence, the potential benefits of SI development interventions cannot be adequately evaluated using deterministic cost-benefit analysis techniques. Yet, Stochastic Impact Evaluation (SIE) can be effective in guiding investment decisions in such context. In this paper, the social and environmental costs and benefits of introducing spate irrigation system in Turkana County, Kenya was identified. In addition to this, I applied SIE to evaluate the viability of two small scale SI interventions: a project that can irrigate between 50 to 100 hectares (i.e. mini-project); and between 101to 200 hectares (medium-project). I elicited experts' knowledge to develop a causal intervention decision model (i.e. including all the benefits, costs and risks) and to collect the estimates for all input variables. Model results indicated that both SI projects are beneficial to the local community and the environment. The communal and environmental benefits is positively correlated with the size of the spate irrigation. However, the overall project's benefit to cost ratio is negatively correlated with the size of the spate scheme. Furthermore, the likelihood of generating negative outcome increases with the increase in the size of the spate. The study suggests that investment in small spate irrigation scheme is likely to generate positive outcome and it is also a cost effective alternative. The study provides crucial information which supports the decision making of implementing SI interventions. It also demonstrates a comprehensive approach to evaluate and prioritize complex and uncertain development interventions, even in data scarce dryland areas.

Keywords: Dryland development, ex-ante assessment, flood-based livelihood, water harvesting, probabilistic assessment

6.1. Introduction

Climate change and variability manifested by changes in the amount, intensity and distribution of precipitation and temperature adversely affects household welfare, food security as well as national economic growth (Brown et al., 2011; Wossen and Berger, 2015; Haile et al., 2017; Lewis, 2017; Wossen et al., 2018). In particular, dryland (i.e. arid and semi-arid) communities are highly vulnerable to the impacts of climate change, as climate change is expected to bring warmer temperatures, erratic rainfall patterns and extreme weather events such as flooding and drought (Rufino et al., 2013; Tsegaye et al., 2013; Wheeler and von Braun, 2013; Schilling et al., 2014; Opiyo et al., 2015). In Kenya, dryland areas are already experiencing moisture stress due to climate change induced evapotranspiration (Rockström et al., 2010; Morton and Kerven, 2013). These patterns are expected to impede the development prospects of these communities and worsen the already precarious food insecurity situation as pastoralism and agro-pastoralism, which are heavily reliant on water and/or moisture availability, forms the basis of livelihood (Nassef et al., 2009; Rufino et al., 2013; Tsegaye et al., 2013; Schilling et al., 2014; Opiyo et al., 2015; Egeru, 2016).

Among extreme weather events, drought is considered to be the main cause of productivity loss, food insecurity, and poverty (Huho and Mugalavai, 2010; Nicholson, 2014; Opiyo et al., 2015). For example, Kenya has experienced more than 28 drought events over the last 100 years (Huho and Mugalavai, 2010). Further, future climate projections suggest increasing frequency of extreme drought and flooding events, especially in the drylands, including Kenya (Nassef et al., 2009; Serdeczny et al., 2016). If proper adaptation measures are not implemented climate shocks will aggravate the problem of food and nutrition insecurity (Nassef et al., 2009; Whitfield and Reed, 2012; Morton and Kerven, 2013; Egeru, 2016). For example, the effect of 'meteorological calamities' (i.e. flood and drought) during 2010/11 in Kenya devastated the livelihood of the local communities and this was severe in the northern parts, such as Turkana county (Nicholson, 2014). During this time, Turkana county experienced the worst drought over the last 60 years, yet, the county had normal to moderate rainfall (Opiyo et al., 2015). However, the drought as well as flood impacts could have been minimized by constructing an effective structure that harvests flash floods for economic use, such as reservoir (Gebregziabher et al., 2009; Zhang et al., 2018), or spate irrigation (SI) systems (Mehari et al., 2011; van Steenbergen et al., 2011;

Hagos et al., 2017). Moreover, as pastoralist and agro-pastoralist communuities increasingly compete for depleting land and water resources, violent conflicts might escalate (Schilling et al., 2014).

Spate irrigation (SI) is one of the oldest irrigation system and has been practiced for more than 7000 years (Mehari et al., 2011). SI involves harvesting flash floods originated from inundated dry river beds and spreading into farming, grazing, and/or (agro)forestry area (Mehari et al., 2011; van Steenbergen et al., 2011). SI systems play a vital role in moisture stressed drylands where the development of other irrigation and water harvesting interventions are either expensive or constrained by capacity, technology, and physical availability (Komakech et al., 2011; Erkossa et al., 2014). While achieving positive climate outcomes, SI can help to reduce natural resource depletion, prevent community clashes, drive intensification of livestock crop production systems, and ultimately help to reduce poverty and food insecurity in the country (Hagos et al., 2017; Zimmerer, 2011). For instance, it supports the livelihood of 13 million marginalized, resource poor, and economically disadvantageous people in 20 countries (Mehari et al., 2011). Globally, 2.6 to 3 million hectare of land are under SI systems (Mehari et al., 2011; van Steenbergen et al., 2010). Despite the invincible potential and suitability of SI systems for topographic setting of dryland agroecology (Mehari et al., 2007; van Steenbergen et al., 2010), less attention is given to it (Mehari et al., 2011).

Implementation of SI development interventions in dryland areas, such as Turkana, requires a detailed ex-ante assessment. Accordingly, intervention decisions should capture its wider social, political, and environmental impacts (van Steenbergen et al., 2010), which is often neglected during evaluation (Luedeling et al., 2015; Whitney et al., 2017). In addition, investment in SI systems are risky and sensitive to hydrological uncertainties (van Steenbergen et al., 2011), in which its performance depends on the volume of flood harvested (Tesfai and Stroosnijder, 2001; Mehari et al., 2011; van Steenbergen et al., 2011). The flood is, however, unpredictable both in time, frequency and volume (Mehari et al., 2007; van Steenbergen et al., 2010). Thus, evaluating SI interventions through applying commonly used deterministic cost-benefit analysis is ineffective. Because assessments carried out with single estimates, mostly average value, masks uncertainties and heterogeneities and hence might mislead decision makers (Berger et al., 2017). Furthermore, decision-makers are often constrained by data scarcity, lack of tools to integrate available information, and inherent uncertainty to make wise and informative decisions (Peterman and Anderson, 1999; Luedeling et al., 2015). This is specifically challenging in drylands, such as Turkana, where the pastoralists travel to different locations and survey based data collection is either expensive or inconvenient (Smith et al., 2000). Against this background, in this paper I make use of a Stochastic Impact Evaluation (SIE) approach that captures system complexity, uncertainty, and overcomes data scarcity challenges (Luedeling et al., 2015; Whitney et al., 2017; Wafula et al., 2018). SIE is a probabilistic simulation that quantitatively captures uncertainty and variability of parameters and generates a plausible range of project outcomes that support decision-making processes (Rosenstock et al., 2014; Wafula et al., 2018).

Taking SI investment decisions can be complicated by the deep uncertainty surrounding biophysical and socio-economic factors. Robust decision-making techniques can help address this problem and ensure that investments are 'robust' to a range of future scenarios. In this paper, I used a SIE approach to evaluate the viability of implementing SI development interventions in Turkana county, Kenya. I consider two small-scale SI interventions that vary based the command area irrigated: under 100 (hereafter referred as mini-project) and under 200 hectares (hereafter referred as medium-project). SIE tools were used to project the expected SI intervention outcomes (i.e. communal, environmental, and total project outcome) as well as identify critical uncertainties that highly influence the outcomes and may be required for further measurement. In addition, the study also prioritized the two alternative projects based on projected expected outcome.

6.2. Methods and Materials

6.2.1. Location

The SI considered in this study is in Turkana County, northwestern Kenya. It is the largest County (77,000 km^2), situated between 1^o 30' and 5^o 30' North and 34^o 30' and 36^o 40' East (Turkana County Government, 2013). The County has a bi-modal, but erratic and unreliable rainfall, with annual minimum and maximum rainfall ranging between 52 and 480 mm and the average annual rainfall amounting 200 mm (Yazew et al., 2014b). The County is characterized as dryland with the temperature ranging between 20^{o}c and 41^{o}c (Turkana County Government, 2013). Based on the 2009 census result, Turkana has a population of 855,399; and by 2018 it is expected to exceed 1.5 million (Turkana County Government, 2013). According to the Kenyan wellbeing survey report of 2015/16 (KNBS, 2018), the County has the highest rate of poverty and constitutes 15% of the 3.9 million people living under extreme poverty in Kenya.

The Turkana integrated development plan seeks to minimize drought and flooding impacts by investing in water harvesting technologies and irrigation development (Turkana County Government, 2013). The county is dominated by low lying (flat) open plains with mountain ranges (Yazew et al., 2014b), which is suitable for SI practices (c.f. Mehari et al., 2011; van Steenbergen et al., 2010). The potential bright spots for SI systems in Turkana country had assessed by Mekelle university (Yazew et al., 2014b). The topographic setting as well as rainfall status was taken into consideration during suitable site selection. Accordingly, nine potential sites were identified (i.e. Kaapus, Nakibuse, Kobuine, Lomidat-1, Lomidat-2, Natira (Lokipoto), Nakatwan, Kalapata, and Kospir).

6.2.2. Decision framing and model development

The first approach in conducting the decision focused research is clearly articulating the decision of the proposed intervention. Accordingly, the decision was to know whether the introduction of SI intervention is viable in Turkana. This decision should be done by comparing the streams of costs and benefits of the proposed intervention after considered the risk of the proposed intervention and the time value of money. In this study I consider both mini and medium-projects that targeted for crop production purpose. The proposed intervention is expected to affect the community, the environment, and the implementer who fund the introduction of the spate system. Thus, we simulated the expected outcome of the proposed intervention on the community, environment, and the implementer. The individual outcomes were, then, summed up to see the overall outcome of the proposed intervention. Thus, I computed the expected outcome of these effects for each intervention separately. I prioritized the intervention that maximizes the expected utility, which is the sum of all expected outcomes, which is expressed as net present value and benefit to cost ratio.

6.2.3. Expert knowledge elicitation

I used expert knowledge (Tamene et al., 2011; Rosenstock et al., 2014; Wafula et al., 2018) to develop the decision model and collect quantitative estimates about the SI interventions. Eight subject matter experts, in which four of them trained about SI at Mekelle University, Ethiopia, were selected from the County's irrigation development and land reclamation office. A three-day decision modeling workshop was held on the first week of May 2018 at Lodwar, Turkana. During the workshop, the experts identified all the benefits, costs, and risks of the proposed project and built a quantitative decision model. The models were iteratively refined until the experts felt confident that all the input variables and its relationships was identified (Luedeling et al., 2015). In addition, formal "calibration training" (Hubbard, 2014) was given to all experts. The training allows experts to minimize bias as well as estimation error and provide an estimate that accurately capture their individual state of uncertainty (Luedeling et al., 2015; Whitney et al., 2017; Wafula et al., 2018). To capture the experts' state of uncertainty in all input variables, they provided an estimate with a range of values based on 90% degree of confidence, which has been used in different studies (c.f. Rosenstock et al., 2014; Luedeling et al., 2015; Whitney et al., 2017; Wafula et al., 2018). This indicates that, the experts were 90% certain that the actual value lay within the given range of estimates. Accordingly, the estimates for all input variables were collected following this procedure (see appendices **Table A-5**).

6.2.4. Simulation modeling

The decision models were scripted in R programming language (R Core Team, 2022). I used the decisionSupport package in R (Luedeling et al., 2022). For a likely correlated set of variables, certain correlation requirement was met by introducing a coefficient of variation into the randomly drawn values (Luedeling et al., 2015). Moreover, the monetary estimates were changed from Kenyan shilling (KSh) into US dollar at a rate of $1=100 KSh, which was the exchange rate during the time of data collection.

I conducted 10,000 Monte Carlo simulation runs for both mini and medium-projects (Platon and Constantinescu, 2014; Rosenstock et al., 2014) to determine the distribution of the plausible outcomes, in terms of Net Present Value (NPV) and Benefit-Cost ratio (BCR), by randomly selecting the value from the defined distribution of the input variables (Luedeling et al., 2015; Whitney et al., 2017). The NPV was computed for each of the communal, the environmental, and the implementer's expected effects by discounting the respective projected annual net cash-flows. The overall project NPVs for each intervention were calculated by summing up the corresponding communal, environmental and implementer's NPV. In addition, the BCR for each project was computed by dividing the corresponding sum of communal and environmental NPV to the total project cost (i.e. the implementer's NPV).

The key sensitive parameters that influence the distribution of project outcome was identified using Partial Least Square (PLS) regression, in which the total project NPV for each intervention were regressed to all input variables (Luedeling and Gassner, 2012; Luedeling et al., 2015; Wafula et al., 2018). I use the output of the PLS regression, which expressed as variable importance in the projection (VIP) score (Farrés et al., 2015) to select the critical uncertain variables (i.e. with a score of above 0.8).

Reducing the uncertainty in each of the sensitive variables may not increase certainty to the anticipated project outcome (Wafula et al., 2018). Accordingly, Value of Information (VoI) analysis (Tuffaha et al., 2016) was carried out to identify the critical uncertain variables in which their further measurement increases certainty to the total project outcome. This approach guides decision-makers to target their further study only on the variables that have information value and reduces the chance of making wrong decision (Whitney et al., 2017). The value of integrating additional information for each of the identified uncertain variable, which expressed as the expected value of perfect information (EVPI), was computed following the procedure described by Wafula et al. (2018). EVPI is the difference between the project's NPV after integrating additional information and the value under the current uncertainty or imperfect information (Hubbard, 2014; Luedeling et al., 2015; Whitney et al., 2017, 2018).

6.3. Results

6.3.1. Expert knowledge elicitation result

All the plausible social and environmental costs, benefits, and risks of implementing the SI development in Turkana were identified by experts and incorporated into a decision model that illustrated the expected impact pathway (**Figure 6-1**). The proposed SI intervention have an impact on the community, the implementer who fund the SI, and the environment. The experts identified six benefits, fifteen cost and seven risks (**Table 6-1; Table 6-2**).

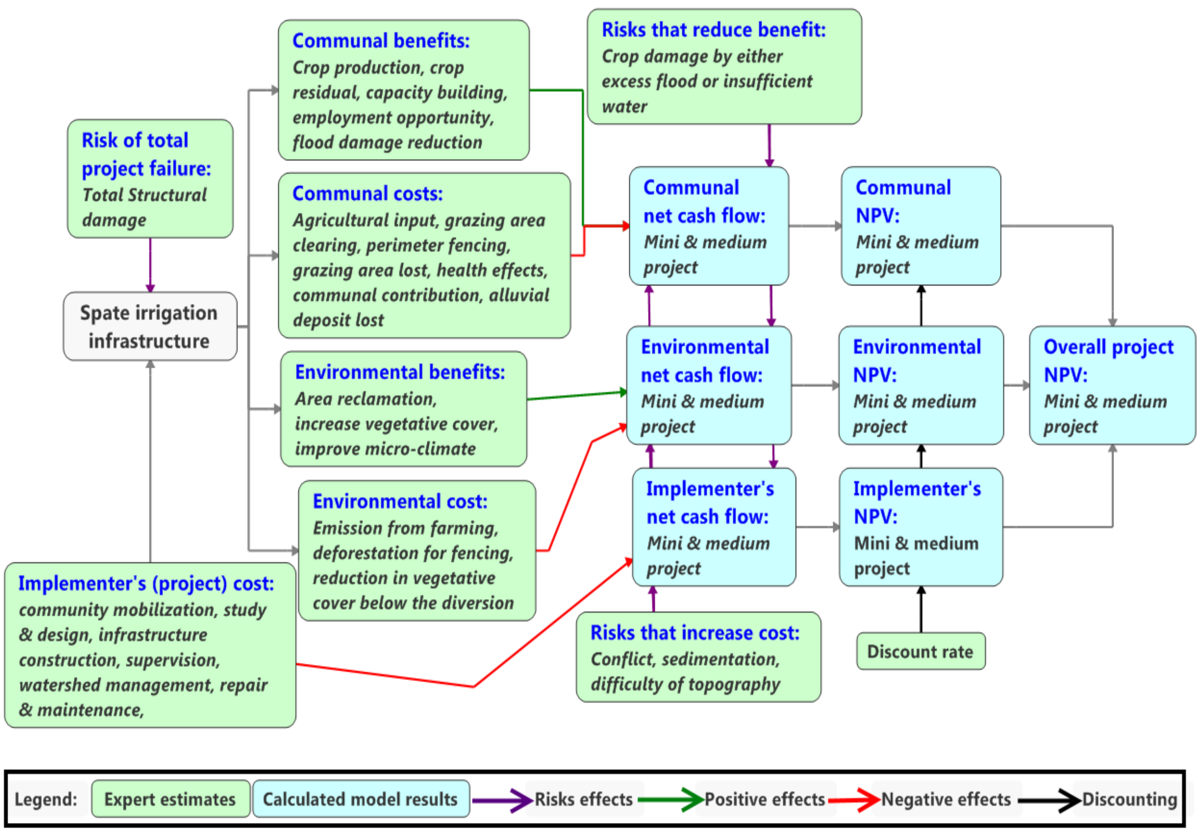

Figure 6-1. General structure of the decision model for spate irrigation in Turkana, Kenya

General structure of the decision model representing all important costs, benefits, and risks identified by local experts for the implementation of Spate irrigation project in Turkana, Kenya. The model is structured as an impact pathway from the decision to introduce spate irrigation (left) through all estimated and risk-adjusted net cash flows to the final model outputs in the form of Net Present Value (NPV).

The proposed SI intervention benefit agro-pastoralists as well as pastoralists willing to diversify their livelihood strategy (i.e. the target group) from the crop and residue production. Expert estimated productivity per hectare is between 0.9 and 1.8 tons of crop and 2.7 and 5.4 tons of crop residue. The project will also create, both on and off-farm employment opportunities for the local community. Moreover, the diversion and spreading of flash floods in to the command area will reduce the risk of flood damage in the downstream area. Yet, the proposed intervention will cost farmers for farm inputs, perimeter fencing, and grazing area clearing costs. Furthermore, the expected land use change (i.e. from grazing to farming area) will affect the pastoral community.

Table 6-1: The costs and benefits of introducing spate irrigation in Turkana

The expected costs and benefits of spate irrigation intervention	Expected impact dimension		
	Communal	Environmental	Implementer
Benefits of spate irrigation			
Increase in agricultural production (grain & residue)	Yes	–	–
Employment opportunity	Yes	–	–
Capacity building through training	Yes	–	–
Reducing in Flooding effect	Yes	–	–
Increase in area reclamation and vegetation cover	–	Yes	–
Improve in micro climate	–	Yes	–
Costs of spate irrigation			
Agricultural input cost	Yes	–	–
Loss of pasture area due to area conversion	Yes	–	–
Pasture area clearing cost	Yes	–	–
Perimeter fencing of farming plot	Yes	–	–
Human health deterioration (infestation of malaria and other water borne disease)	Yes	–	–
Loss of fertile alluvial deposit	Yes	–	–
Labour contribution for repair and maintenance of the structure	Yes	–	–
Deforestation for perimeter fencing	–	Yes	–
Soil disturbance and emission from farming	–	Yes	–
Reduction in vegetation and forest cover in the downstream area	–	Yes	–
Study and design	–	–	Yes

The expected costs and benefits of spate irrigation intervention	Expected impact dimension		
	Communal	Environmental	Implementer
Community mobilization, training, and awareness creation	−	−	Yes
Construction of the flood diversion structure	−	−	Yes
Catchment restoration	−	−	Yes
Repair and maintenance	−	−	Yes

The expected costs and benefits of introducing spate irrigation intervention in Turkana County of Kenya. These effects are identified by the experts during the workshop. In the table, "Yes" represents that the typical effect is considered in the specified impact dimension, and "−" is not applicable.

To introduce the SI system in Turkana county, the implementer is expected to cover the construction cost of the flood diversion structure. The suitable site assessment and preparation of site specific design as well as the supervision of the construction is also to be covered by the implementer. Furthermore, the implementer is also expected to incur costs for mobilizing the communities, providing capacity development trainings and raising awareness of SI in the intervention area

The experts identified watershed management practices as integral part of SI practices, which in turn have an environmental benefit through increase in vegetation cover that reduce soil erosion and enhance the reclamation of adjacent degraded areas. Moreover, the experts identified deforestation for perimeter fencing of cropping area, additional emission from farming practice, and reduction in vegetation cover further below the diversion structure as environmental costs of implementing the intervention.

The type of risks that can compromised the expected impact of introducing spate systems are also identified (**Table 6-2**). According to the experts, some of the topographic setting of Turkana county are mountainous, which in return lead to higher cost of constructing long flood diversion structures. The risk of improper design, interpretation, and implementation can also lead to total structural failure, which in return reduce the expected benefits from the intervention. Furthermore, the risk of dry spell or drought as well as excessive rainfall affects the expected benefits of the proposed SI intervention.

Table 6-2: The type of risks identified by the experts for introducing spate irrigation intervention

Type of risks of spate	Expected impact of the risk		
	Increase cost	**Reduce benefit**	**Total failure of structure**
Unsuitable and/or sloppy topography	Yes	−	−
Lack of proper design and planning	Yes	Yes	Yes
Poor interpretation and implementation of design	Yes	Yes	Yes
Conflict	Yes	−	−
Sedimentation and/or siltation	Yes	−	−
Dry spell and drought	−	Yes	−
Excessive rainfall and flooding that damage crops	−	Yes	−

The type of risks identified by the experts for the implementation of spate irrigation intervention in Turkana County, Kenya. In the table, "Yes" represents that the typical risk has corresponding impact, while "−" is not affect.

6.3.2. Simulation results

6.3.2.1. Projected spate irrigation development outcome

The Monte Carlo simulation results reveal that both types of the proposed SI interventions are likely to be beneficial to the local community and the environment (**Figure 6-2**; **Figure 6-3**). Under both mini and medium-project, the communal and environmental NPV are positive in 99.5% of the total model runs. Based on 5th and 95th distribution of the project outcome, the communal NPV under mini-project is between \$397 thousand and \$1.39 million (**Figure 6-2**), while the NPV from the medium-project is between \$726 thousand and \$2.66 million (**Figure 6-3**). In addition, the environmental NPV under mini and medium-project lies within a range of \$14 to \$54 thousand and \$19 to \$102 thousand, respectively. The mini-project costs the implementer between \$107 and \$387 thousand, whereas it is between \$368 thousand and \$1.73 million for the medium project.

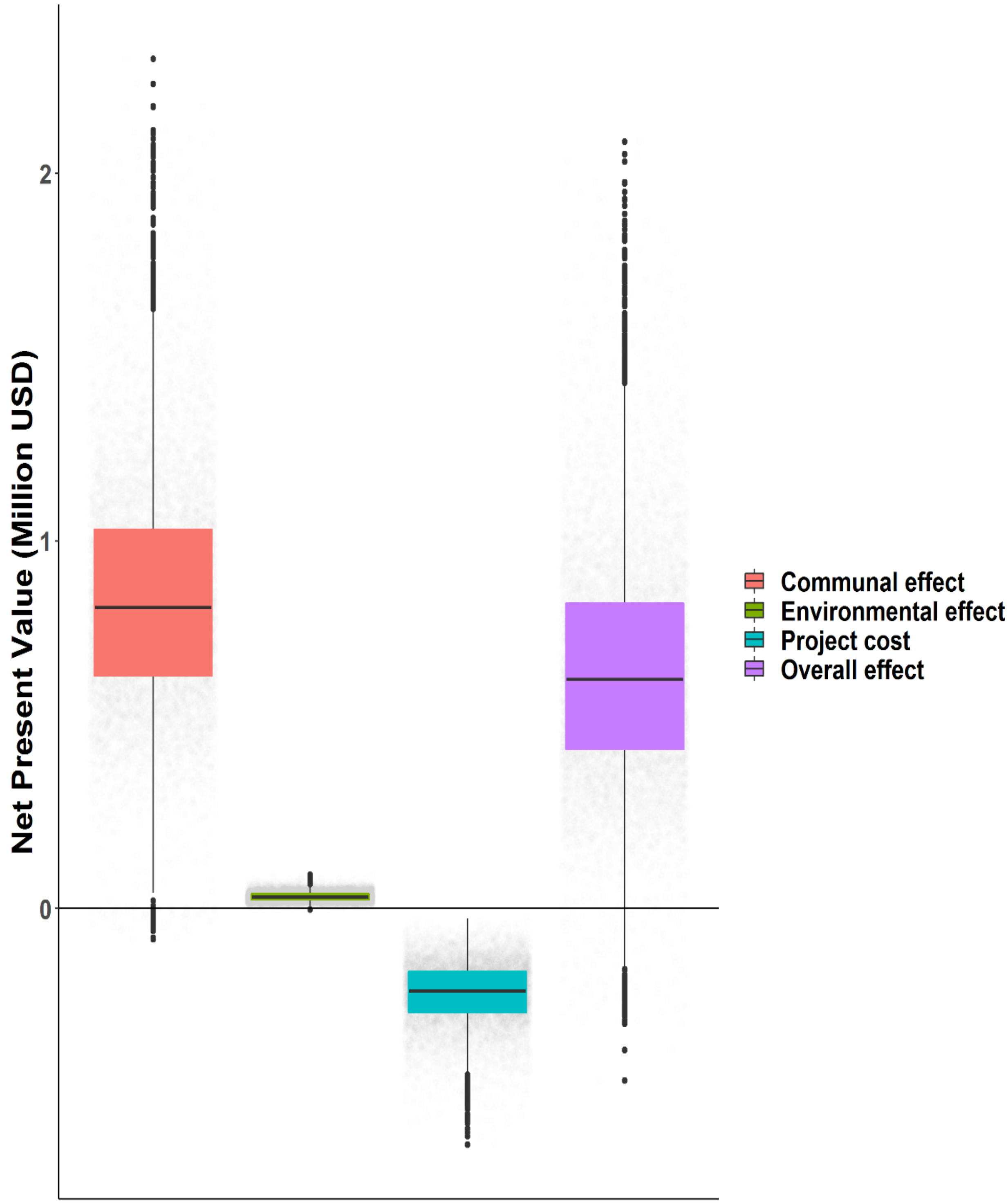

Figure 6-2: Distribution of the expected outcomes for introducing mini-spate irrigation in Turkana

Distribution of project NPV based over 10,000 Monte Carlo model runs for all the community, the environment, the implementer, and the total project outcomes for mini spate irrigation development that can irrigate between 50 to 100 ha of land in Turkana County, Kenya.

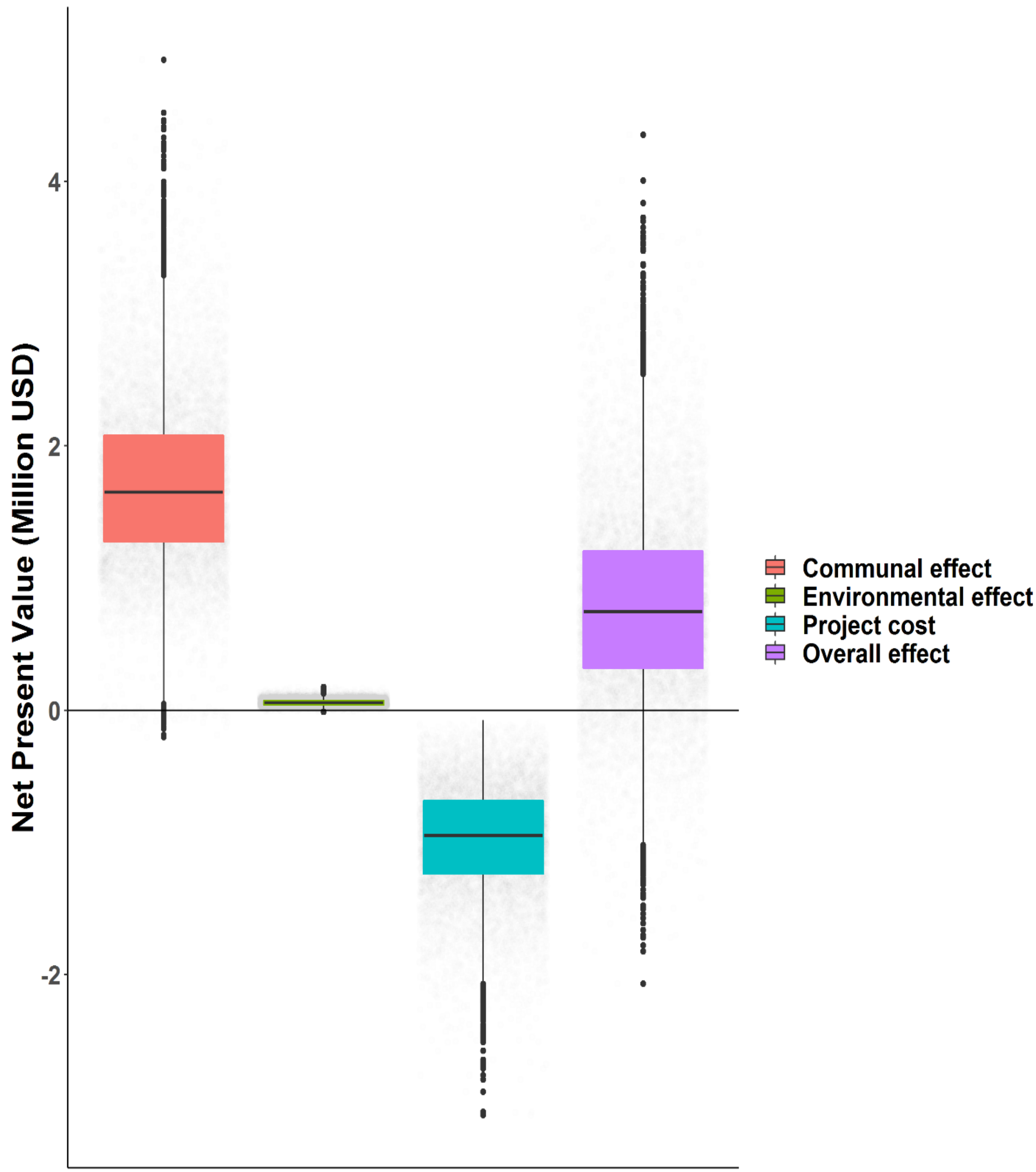

Figure 6-3: Distribution of expected outcomes for introducing medium-spate irrigation in Turkana

Distribution of project NPV based over 10,000 Monte Carlo model runs for all the community, the environment, the implementer, and total project outcomes for introducing medium spate irrigation development that can irrigate between 101 to 200 ha of land in Turkana County, Kenya.

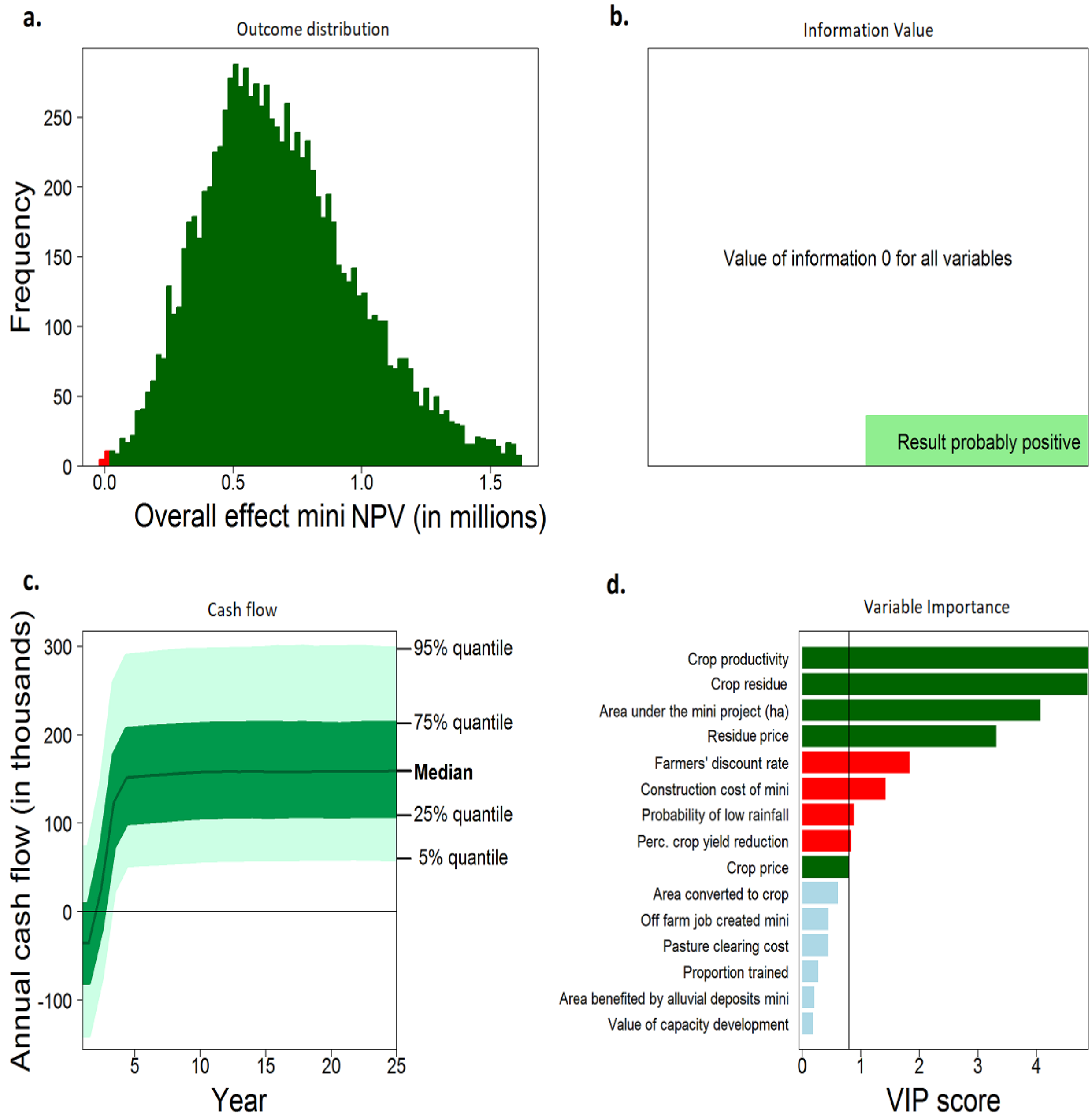

Figure 6-4. Distribution of outcomes for introducing mini spate irrigation intervention

*Results of 10,000 Monte Carlo model runs for the total project outcomes of implementing the proposed mini spate irrigation development project in Turkana, Kenya. **a**. distribution of project outcome expressed in NPV, positive (green) and negative (red). **b.** Expected Value of Perfect*

Information (EVPI). EVPI>0 indicates that the selected uncertain variable has information value and further measurement is recommended to reduce model uncertainty. ***c.*** *distribution of modeled annual net cash flow over the expected project life span of 30 years.* ***d.*** *variable of importance in projection (VIP) showing all model variables with a VIP greater than 0.8 (gray vertical line) and correlation with project outcome, positive (green) and negative (red).*

In general, the overall project NPV for mini-project was highly certain (i.e. positive value generated in 98.9% of the total model runs) with a value between $196 thousand and $1.19 million (**Figure 6-2**; **Figure 6-4a**). While, under medium-project it ranges from a loss of -$407 thousand to $1.83 million (**Figure 6-3**). Furthermore, the BCR was higher under mini-projects. Based on the 5^{th} and 95^{th} distribution, the BCR under mini-project is between 1.8 and 8.3, while the corresponding values for the medium-project ranges between 0.8 and 5.0.

6.3.2.2. Sensitive parameters

The PLS results reveal that the distribution of the total project outcomes under both mini and medium-project were positively influenced by the uncertainty in the per hectare farm revenue (i.e. crop and residue productivity, the corresponding prices), and the total command area parameters (**Figure 6-4d**; **Figure 6-5d**). However, it was negatively correlated with the uncertainty in the construction cost of diversion structure, the yield reduction due to insufficient floodwater, and the farmers discount rate parameters.

6.3.2.3. Variables with information value

The VoI result indicated that the uncertainty on the per hectare crop and its residue productivity under medium SI project had higher EVPI, indicating that further measurement of the crop and its residue productivity were recommended to increase certainty of the project outcome (**Figure 6-5b**). Nevertheless, the EVPI for mini-project was zero and further measurement of the uncertain parameters were not change the current recommendation on the preferred decision option (**Figure 6-4b**).

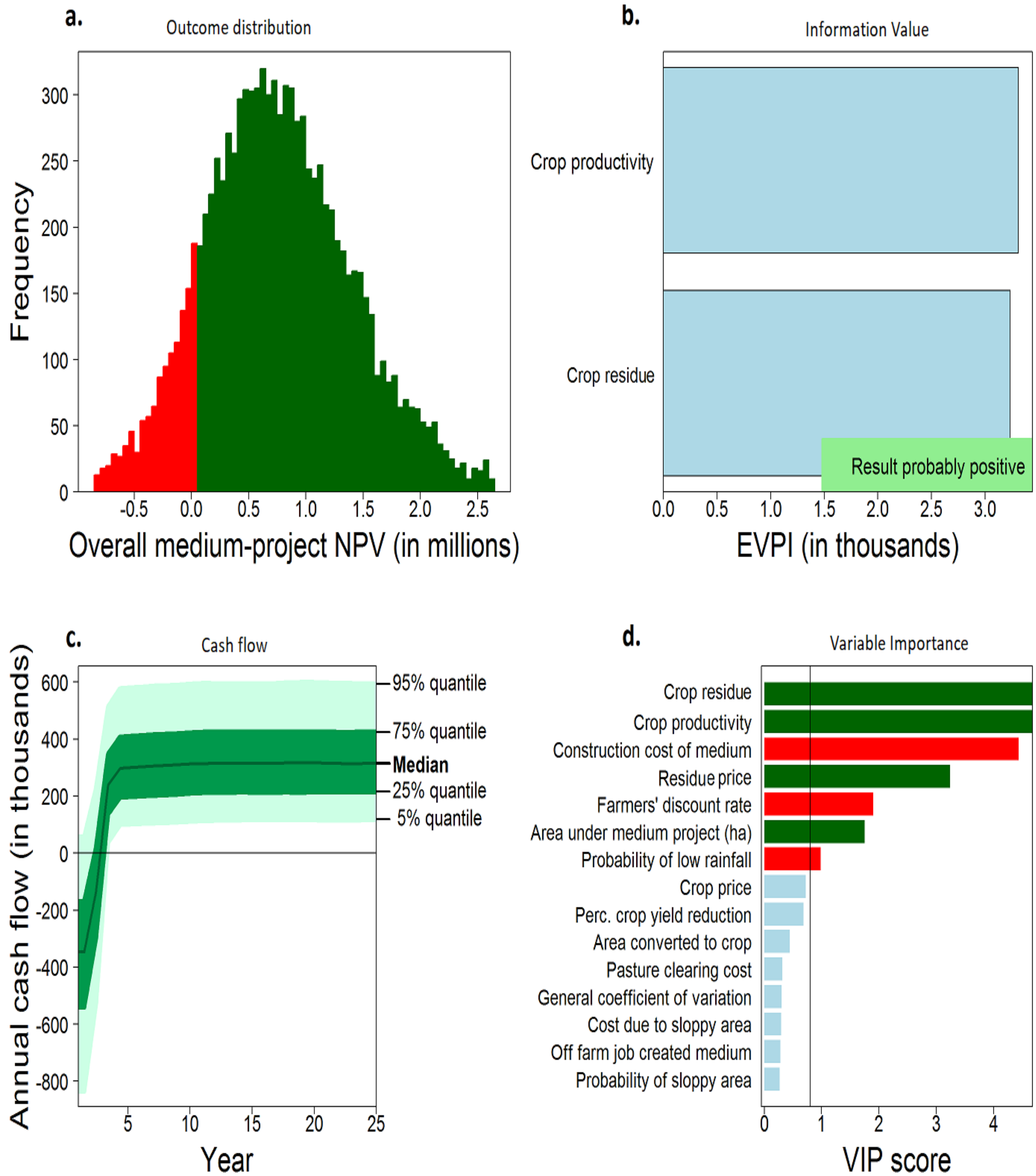

Figure 6-5. Distribution of outcomes for introducing medium spate irrigation intervention

Results of 10,000 Monte Carlo model runs for the total project outcomes of implementing the proposed medium-spate irrigation development project in Turkana, Kenya. For detailed description of the graphs and bars, see legend to **Figure 6-4**

6.4. **Discussion**

6.4.1. Spate irrigation outcomes

Majority of the Turkana dwellers are dependent in animal husbandry. Accordingly, Spate irrigation intervention is new to the Turkana county. Even if it is new to the area, the model result indicates that an introduction of SI development interventions in Turkana county have high likelihood of benefiting the local community as well as the environment. The communal as well as the environmental effect of Spate systems are correlated with the size of the structure. Accordingly, increasing the size of the spate system, which in return also leads to increase in command area, is leading to higher communal benefits. Doubling the command area under the spate system leads to almost double (83% to 91%) of communal benefit. This might be due to high revenue from crop and its residue production which is strongly connected to the total command area under the scheme, which is also the most significant parameters that influenced the simulated project outcome. In addition, a larger volume of floodwater will be harvested to irrigate the expected area under a bigger spate system, which in return, reduces the risk of flood damage in the downstream (i.e. below the SI scheme) area (Zhang et al., 2018). Moreover, channeling investments to the community have a multiplier effect in the economy (van Steenbergen et al., 2010); and in this case under larger scheme, the local community will have better effect through creating on and off-farm employment opportunities. This, in general, suggests an increase in the size of the intervention leads to higher communal benefits.

SI development project improves food security and reduces poverty (Zimmerer, 2011; Hagos et al., 2017). Although quantifying the effect of these alternative interventions on poverty reduction was beyond the scope of this study, the poverty reduction effect under larger scheme is expected to be higher than smaller projects. Because under larger spate systems, the agricultural production as well as household income is higher, and this significantly diminishes household food insecurity and poverty level (Hagos et al., 2017). Therefore, introduction of Spate systems is important to increase household income for the Turkana communities.

The annual and seasonal variation in crop productivity and cropping area affects the economic benefits of SI interventions (van Steenbergen et al., 2010). The common crops in Turkana are sorghum, millet, and maize (Turkana County Government, 2013). Although these crops grow easily under spate systems (Mehari et al., 2011; van Steenbergen et al., 2011), the yield estimates used in this study is far below the productivity of these crops under SI system in other countries (c.f. Puertas et al., 2015). Moreover, a production of once per year was considered, but farmers can harvest two or more times per year using better conservation of the residual moisture and plantation strategies (Tesfai and Stroosnijder, 2001; Muthigani, 2011; van Steenbergen et al., 2011). For example, farmers may plant sorghum during short rainy season and maize during long rainy season (Muthigani, 2011). Thus, the outcomes of the SI could be increased through increasing crop productivity and increasing number of harvests per year.

The yield reduction effect of less flood diversions due to either below the expected minimum threshold of precipitation or low conveyance efficiency (van Steenbergen et al., 2010) influences the SI project outcomes negatively. The performance of SI system is directly related to the volume of floods harvested (Tesfai and De Graaff, 2000; Komakech et al., 2011). If less flood (i.e. during bad season) is diverted into the farming plot, only few farmers, especially those who get flood first, could irrigate their farms and produce some crops or fodder (van Steenbergen et al., 2010). Therefore, for successful SI intervention, the uncertainty in the precipitation and runoff should be carefully addressed during the planning phase.

Catchment area restoration and conservation practices that reduce the sedimentation problem is an integral part of the SI system (van Steenbergen et al., 2010, 2011; Mehari et al., 2011). On top of sediment reduction, the rehabilitation practice leads into area reclamations, increase in vegetative cover, and improve in micro climate (Wolancho, 2012). Having the same precipitation and irrigation efficiency for both projects, a bigger watershed area is required to irrigate the command area under medium-project. According to model result, the environmental benefit was reduced by 38 to 87% when the spate scheme is declined by half. This suggest that in well planned spate systems, an increase in the size of the scheme is likely to increase environmental income. Thus, catchment restoration should be at the center of spate system develop intervention.

Despite of higher communal and environmental benefits, larger project interventions needs a higher investment cost. Construction cost significantly increases with the size of the scheme (van Steenbergen et al., 2010; Chukalla et al., 2013). In SI, there is no economy of scale, because larger structures are more complex and needs additional investment for construction of cross-river siphons, long flood channels, and sedimentation structures that help to withstand and divert a large volume of floods (van Steenbergen et al., 2010). Thus, the implementer is expected to invest a large sum of money for a larger project, which in turn leads to higher loss to the implementer. The implementers, mostly in developing countries, are investing Spate systems for the betterment of the population; and, accordingly, there is no any direct implementer's benefit considered in this study. Yet, the implementer will benefit from ensuring food security, reducing poverty, and political stability. In addition, SI development practices are linked with increment in settlements (van Steenbergen et al., 2011) and development of social networks (Zimmerer, 2011). Accordingly, the implementer (government) could benefit by reducing the transaction cost to provide social services (e.g. schools, hospital or clinics, and framers training schools) and easily disseminate the required information. The community could also benefit from these social services as well as the information. Thus, considering these benefits, which I did not capture in this study, could lead to higher project outcomes. Therefore, the implementer should compare the value of the investment before deciding based on this simulation results.

In general, the aggregated outcome for the implementation of SI interventions indicated that the overall economy of Turkana county is likely to increase using the Spate systems. The model result suggested that larger SI systems have relatively higher effect on the economy (i.e. considering only the magnitude). Yet, the outcome (NPV) for larger SI systems is uncertain. According to the VoI result, the knowledge gap on farm productivity (i.e. crop yield and residue) should be narrowed down to make final decision of larger structures (**Figure 6-5b**). Because further study of these parameters increases certainty to the total project outcome, this in return, helps decision makers to select the optimal option (Wafula et al., 2018). Therefore, the decision maker should study the farm level productivity before approving the project based on the current model generated recommendation.

Furthermore, the BCR result revealed that for an equivalent of investment outlay, smaller SI intervention has generated higher benefits to the society. According to the result, for an equivalent investment in spate systems, smaller project returns a benefit of 1.8 and 8.3 times the investment cost, while doubling the size of the land generates a benefit of between 0.8 and 5.0. Moreover, the chance of generating negative outcome is directly related to the size of the structures (i.e. an increase in the size of the structure leads to high likelihood of generating negative NPV). Accordingly, the result indicated that investment in in smaller spate systems are economical, because (i) the expected benefits from larger SI development intervention can be attained with less investment in serious of small spate schemes; and (ii) a large number of smaller SI structures can be constructed with the expected investment for larger structures, which in return lead higher societal benefit. However, the topographic setting of the area should be considered during construction.

In general, the results of the study revealed that, investment on modern SI in arid and semi-arid areas could increase local food production and household income, reduce risk of flood damage, and improve the environment. The study revealed that although larger SI projects have better effect on the local community and the environment, smaller project can generate higher return for an equivalent of investment outlay. Furthermore, the outcome for investment in smaller SI scheme is certain. Thus, investment in smaller SI project is viable, based on current state of expert understanding. This is mainly due to higher project cost of constructing larger spate systems. In SI, there is no economy of scale; and the per hectare equivalent cost of constructing the structure significantly increases with the size of the scheme (van Steenbergen et al., 2010). Because to irrigate a big area of farm land it required a special structure that enable to withstand and divert a large volume of flood, which is mostly complex and costly (ibid). Moreover, improving annual crop yield through either utilizing yield enhancing technologies or increasing the annual frequency of cropping is essential to increase the outcome of SI systems. In addition, the risk of insufficient flood affects the performance of SI intervention negatively; and the uncertainty in precipitation and runoff should be carefully addressed during the planning phase.

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CHAPTER SEVEN: GENERAL CONCLUSIONS AND POLICY RECOMMENDATIONS

7.1. General conclusions

This PhD thesis evaluated the economic viability of an irrigation dam construction intervention, road-water harvesting, and an introduction of spate irrigation development interventions in Tigray region of Ethiopia and Turkana County of Kenya, respectively using SIE techniques. The study explicitly considers an irrigation dam construction intervention as well as road-water harvesting intervention in Tigray region of Ethiopia and spate irrigation development intervention in Turkana county of Kenya as case studies. Using the SIE tools (i.e. Monte Carlo simulation, Partial least square regression, and Value of Information analysis), the study sought to (i) assess the economic viability of the selected rainwater harvesting and irrigation development interventions; (ii) identify the most influential parameters that affect the intervention decision; and (iii) identify the critical knowledge gap that needs further measurements.

In the results explicated in Chapter four, the construction of an irrigation dam in Tigray is likely to generate benefit for all stakeholders in the community (i.e. downstream irrigators and non-irrigators, displaced farmers, and upstream non irrigators). However, the high investment cost of constructing the structure is likely to lead to negative total project outcomes. Complementing the dam construction with effective catchment restoration could reduce the negative project outcome, but the overall prospects remain negative even then. Thus, based on overall cost-benefit considerations, construction of an irrigation dam in the study area is not advisable.

Net benefits from dam construction intervention in Tigray region of Ethiopia were highest for downstream irrigators, followed by displaced farmers, upstream non-irrigators, and downstream non-irrigators. Farmers with access to the proposed irrigation scheme benefited most. The benefits from irrigation are mostly attributed to increasing numbers of crop harvests per year and reducing crop failure during dry spells. Among farmers who do not have access to irrigation, upstream non-irrigators are expected to benefit more from the proposed dam project than downstream stakeholders. Because the development of the dam may jeopardize the option of downstream non-irrigators to reduce the incidence of crop failure by diverting flash floods into their farming plots (i.e. spate irrigation), which is the common practice in the study area. In contrary to this, upstream villagers will save significant amounts of time by harvesting water from the dam for domestic and livestock consumption, because in the absence of the dam, they have to travel long distances to fetch water. In general, the use of the dam for either irrigation or domestic and livestock consumption is beneficial.

The study also identified the most sensitive parameters that influence the dam construction decision. The *cost of constructing the structure* (i.e. both in terms of the initial estimated construction, inflation, and delay in completion of the structure), the *irrigation inefficiency*, and the *social and cultural value of the displaced people* were the most sensitive parameters that affect the simulated project outcome negative. However, the *price and maximum yield of vegetables*, the *maximum irrigable area* under the scheme, as well as the *fruit price* are positively associated with the total project outcome. Furthermore, r*eservoir capacity* as well as the *farm employment opportunity* were positively associated with total project outcome.

Furthermore, the VoI analysis result showed that, the simulated outcome for the displaced farmers was uncertain, because the uncertainty for in the *social and cultural value of the displaced people* needs further measurement before concluding on the initial simulation result.. Accordingly, the reduction in the uncertainty through further measurement of the *social and cultural value of the displaced people* increases certainty to the simulated project outcome for the displaced farmers. However, since measuring this uncertain parameter does not change the simulated outcome for the total intervention decision, spending financial as well as human resources to narrow down the knowledge gap is unnecessary (i.e. information value is zero).

In the fifth Chapter, the economic feasibility of road-water harvesting intervention was evaluated. The experts identified farm pond, percolation pond, and check dam as an important structure to harvest the road-water. Accordingly, the economic feasibility of integrating these water harvesting structures with road construction was evaluated. The model result on road-water harvesting intervention suggest that investments in road-water harvesting structures can play a role in creating resilient societies. The water that drains into or from the roads can provide water for domestic and livestock consumption, enhance agricultural productivity, recharge groundwater, create employment opportunities, reduce flood damage, and save costs, that could otherwise be spent in repairing and maintaining roads that are damaged by floods as well as constructing road detours. However, the benefits from road-water harvesting structures vary with structure type. Hence, the economic viability of integrating the different water harvesting structures with road network expansion varies between the structure types.

Based on the assessment, the communities who have access to the harvested water are likely to be better off when new roads are equipped with water harvesting interventions, whereas such structures incur additional costs for the implementer. In Tigray region of Ethiopia, investment in water harvesting interventions can usually only be made by the government or other development agencies, which implement such projects to strengthen food security as well as create resilient societies. Since the bulk of the investment cost is borne by the implementer, the benefitting communities only need to cover the operating costs, so they are likely to derive net benefits from harvesting road-water. According to model result, harvesting road-water by constructing percolation structures is thus recommendable, whereas the use of check dams seems unlikely to be a profitable investment. Whether net benefits arise from the implementation of farm ponds or a combination of all structure types remains unclear. Because, there are critical uncertainties that needs further measurement before forwarding the initial model generated recommendation. Additional data collection is necessary to come to clear conclusions on these interventions.

The most sensitive parameters that influence the road-water harvesting intervention decision were also identified. The *construction cost of the structure,* the *actual volume of harvestable water,* and the *water holding capacity of the structures* were identified as the most influential parameters in the outcome simulations. Moreover, the percentage of water that is lost through seepage or evaporation and due to inefficiencies was shown to have a strong effect on projected outcomes. Thus, cost-efficient water harvesting structures should be integrated with road construction to increase the expected benefits.

In Chapter six, the streams of costs, benefits and risks of introducing spate irrigation (SI) intervention in Turkana County were identified. All the costs, benefits and risks were then quantitatively estimated and viability assessment was conducted. The expected effect of introducing SI system is on the community, the environment, and the implementer who fund the project. The experts identified fifteen costs, six benefits, and seven risks of introducing the spate system. The communities will benefit from the crop farming, employment opportunities created by having the intervention, capacity development through training, and flood damage reduction by harvesting the floods. The environmental benefits are realized from the catchment restoration, which is an integral part of spate system. The cost of constructing the spate structure (i.e. the study and design, the actual construction cost of the structure, monitoring and evaluation, and repair and maintenance costs), catchment restoration, and mobilizing and training costs are expected to be borne by the implementer. Furthermore, the project will lead the communities to incur additional costs for farm input, land clearing, and perimeter fencing. The value of the land that converted from pastureland to cropping area as well as the value of reduction in alluvial deposit were also identified as communal costs. The deforestation resulted from the forestland, reduction in vegetation and forest in the downstream area, and the soil disturbance and emission were identified as environmental costs of SI system.

The overall simulated model result indicates that an introduction of SI development interventions in Turkana county have high likelihood of benefiting the local community as well as the environment. The communal as well as the environmental effects of spate systems are correlated with the size of the structure. Accordingly, increasing the size of the spate system, which in return also leads to increase in farming area, is leading to higher benefits. The communities can get 83 to 91% higher benefit when the size of the irrigable land under spate scheme doubled. This is due to high revenue from crop and its residue production, which is strongly connected to the total irrigable area under the scheme. In addition, a larger volume of floodwater will be harvested to irrigate the expected area under a bigger spate system, which in return, reduces the risk of flood damage in the downstream area (i.e. below the SI scheme). Moreover, channeling investments to the community have a multiplier effect in the economy; and the local community will have better effect through creating on and off-farm employment opportunities.

In spite of the higher communal and environmental benefits in the Turkana case, larger project interventions need a higher investment cost. Construction cost significantly increases with the size of the scheme. In spate irrigation, there is no economy of scale, because larger structures are more complex and needs additional investment for construction of cross-river siphons, long flood channels, and sedimentation structures that help to withstand and divert a large volume of floods. Thus, the implementer is expected to invest a large sum of money for a larger project, which in turn leads to a higher cost of implementation. Moreover, smaller spate irrigation interventions generate higher benefit to cost ratio, indicating smaller spate irrigation interventions are cost effective for an equivalent investment. More importantly, the chance of generating negative outcome is directly related to the size of the structures. As the size of SI intervention increases, the probability of generating negative outcome is increases.

The yield reduction effect of less flood diversions due to either low precipitation or low conveyance efficiency influences the spate irrigation intervention outcomes negatively. The performance of spate irrigation system is directly related to the volume of floods harvested. If less flood is diverted into the farming plot (i.e. during bad season), only few farmers, especially those who get flood first, could irrigate their farms and produce some crops. Therefore, for a successful spate irrigation intervention, the uncertainty in the precipitation and runoff should be carefully addressed during the planning phase.

In general, rainwater harvesting and irrigation development interventions are likely to benefit the communities, while the overall viability is highly related to the size of the structures. An increase in the size of rainwater and irrigation development structures were likely to led to negative simulated outcome (i.e. NPV). This is mainly due to the higher cost of constructing bigger structures. Furthermore, through the evaluation of the rainwater harvesting and irrigation development interventions, the study demonstrates the applicability of SIE to guide decision-making, under system complexity, input variability, little data availability, and uncertainty. Moreover, all the case studies elucidated expert knowledge to develop an impact pathway model as well as the estimates for all parameters. Though the experts were passed through formal calibration training to calibrate their estimates and reduce individual bias, there is no guarantee that all important aspects of the proposed interventions and their estimates are accurately captured.

7.2. Recommendations for Policy

Investment in rainwater and irrigation development is one of the promising intervention that increase the adaptive capacity of the poor as well as create climate resilient societies. Looking from the results of the study, investment in dam based irrigation intervention could improve the household income as well as food and nutrition security, albeit at the cost of environmental externalities and high investment costs. However, complementing the dam construction intervention with catchment restoration could reduce the expected project losses, because the ecosystem value obtained from catchment restoration is enough to cover some of the costs of the intervention. Thus, the dam construction intervention should be complemented with the restoration of degraded catchment areas. Moreover, the investment outcomes can be improved through reduction of water losses due to inefficiency, targeting high-value crops, and controlling construction cost overruns. Furthermore, the study revealed that the social and cultural costs to the displaced farmers and the wider impact on farmers further downstream, which are often neglected during impact assessments, should be considered in dam based irrigation development interventions.

The future expansion of road networks is likely to have both positive and negative implications. The positive impact of roads is widely recognized and well documented. The negative effect of road construction, especially in terms of adverse hydrological impacts, has only recently gained attention. Communities as well as household assets in the vicinity of roads can be severely affected by the floodwater that drains from roads. However, with the combination of road construction with well-designed water capture structures, these negative impacts can be minimized. Harvesting the road-water that drains into or from the roads with adequate structures is therefore an interesting strategy to create climate-smart or '*green*' roads that benefit the society. However, the structure should be selected and designed based on the prospective return from the proposed investment. Inference to the result, harvesting road-water by constructing percolation structures is thus recommendable, whereas the use of check dams seems unlikely to be a feasible investment.

Water is one of the constraining factor that hinder the economic growth of many dwellers in the arid and semi-arid environment. Investment in water harvesting structures, such as spate irrigation, thus, have paramount importance. Looking at the result of the study, investment in spate irrigation development in arid and semi-arid areas could increase local food production and household income, reduce risk of flooding damage, and improve the environment, while it has also cost to the society and the environment. The viability assessment result revealed that investment in small spate irrigation intervention is certain and cost effective. Therefore, governments and other development agents should prioritize small spate irrigation interventions. Furthermore, to optimize the returns from introducing spate irrigation systems, trainings should be given on cultivating high value crops as well as means of increasing annual cropping frequency. Moreover, success of spate system is highly correlated with the volume of flood harvested to irrigable area; and the uncertainty in precipitation and runoff should be carefully addressed during the planning phase.

The study demonstrates that a decision analysis approach can help overcome some of the weaknesses of commonly used deterministic, *ex-ante* project evaluation techniques (i.e. cost-benefit analysis) by thoroughly capturing all relevant impact dimensions and their inherent uncertainties, addressing system complexity, and confronting data scarcity. The approaches demonstrated in these studies can support decision making for agricultural development investments and provide guidance on resource allocation, even in data scarce environment.

7.3. Recommendations for further studies

The Value of Information analysis identified the critical uncertain parameters that have the potential to change the initially generated model results. For example, the net benefits arise from harvesting road water using farm ponds or a combination of all structure types remains unclear. Additional data collection is necessary to come to clear conclusions on these interventions. Similarly, the outcome from the bigger spate irrigation structure is uncertain and needs further measurement to reduce the knowledge gap in the expected yield from the spate system. Therefore, future research should be carried out to come to clear conclusions.

Spate irrigation can be used for pasture production. Therefore, I encouraged future studies to be carried out to assess the returns from investing in spate systems that divert flash floods into the pasture area in the future. This future study could help me to understand the importance of spate systems in creating climate resilient society. Furthermore, most of the viability assessment of rainwater harvesting and irrigation development interventions were carried out based on the economic and environmental dimensions. Therefore, studies that captured all the impact dimensions should be carried out in the future. This future study will help to clearly articulate the political, social, economic, and environmental impacts of rainwater harvesting and irrigation development interventions.

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Appendices

Table A-1: List of important benefits and costs identified by the experts for the implementation of an irrigation dam project in Tigray, Ethiopia, and applicability to each stakeholder group, the environment, and the implementer

All identified impacts of the proposed dam construction intervention	Downstream irrigators	Downstream non-irrigators	Displaced farmers	Upstream non-irrigators	Environment	Implementers
Benefits of the poposed project						
• Dry season irrigation	Yes	–	Yes	–	–	–
• Supplementing rainfed agriculture during unexpected dry spells in the rainy season	Yes	–	Yes	–	–	–
• Employment generation	Yes	Yes	Yes	Yes	–	–
• Income from compensation payments	–	–	Yes	–	–	–
• Time savings (fetching water and watering livestock)	–	–	–	Yes	–	–
• Access to better infrastructure	–	–	–	Yes	–	–
• Flood control	Yes	Yes	–	–	–	–
• Ecosystem services from catchment restoration (provisioning, regulating and maintenance, and cultural services)	–	–	–	–	Yes	–
• Ecosystem services from restoring vegetation in the vicinity of the reservoir (provisioning, regulating and maintenance, and cultural services)	–	–	–	–	Yes	–

All identified impacts of the proposed dam construction intervention	Downstream irrigators	Downstream non-irrigators	Displaced farmers	Upstream non-irrigators	Environment	Implementers
Costs of the proposed project						
• Dam and infrastructure construction (including study, design, monitoring and supervision)	–	–	–	–	–	**Yes**
• Catchment restoration (soil conservation, reforestation, and area exclosure)	–	–	–	–	–	**Yes**
• Compensation (for farming plot, house and public infrastructure)	–	–	–	–	–	**Yes**
• Repair and maintenance	–	–	–	–	–	**Yes**
• Inputs for agricultural production	Yes	–	Yes	–	–	–
• Additional expenses (e.g. bills for utilities) for displaced farmers who pay for access to new infrastructure	–	–	Yes	–	–	–
• Residence construction (for displaced farmers)	–	–	Yes	–	–	–
• Social and cultural cost of displacement	–	–	Yes	–	–	–
• Loss of agricultural production during construction	–	–	Yes	–	–	–
• Yield reduction further downstream by holding water in the reservoir and catchment	–	Yes	–	–	–	–
• Reduction in alluvial deposits	Yes	Yes	Yes	–	–	–

All identified impacts of the proposed dam construction intervention	Downstream irrigators	Downstream non-irrigators	Displaced farmers	Upstream non-irrigators	Environment	Implementers
• Value of farming area lost to the splitting up between settled and displaced farmers	Yes	–	–	–	–	–
• Ecosystem services forgone from the area under the dam	–	–	–	–	Yes	–
• Ecosystem services forgone from land degradation (i.e. reduction in vegetation, grass, and forest land) due to water storage	–	–	–	–	Yes	–

Yes indicates the identified cost and/or benefit applies for the specific group, while '–' indicates that it does not.

Table A-2: Distribution of Net Present Value (NPV) based on 10,000 Monte Carlo model runs for all stakeholders, the implementer, the environment, and total project outcome for the implementation of an irrigation dam project, including catchment restoration in Tigray, Ethiopia

Description	Distribution of simulation outcome (Million USD)			Chance (%)	
	5%	50%	95%	loss	gain
Environment	3.13	4.56	6.44	0.25	99.75
Downstream irrigators	1.39	3.62	6.16	2.26	97.74
Displaced irrigators	-0.46	0.39	1.01	20.86	79.14
Upstream non-irrigators	0.14	0.29	0.53	0	100
Downstream non-irrigators	-0.27	0.06	0.21	32.32	67.68
Implementer	-17.13	-13.18	-10.67	100	0
Total project effect	**-9.69**	**-4.33**	**0.34**	**93.77**	**6.23**

Note: the chance of loss is the percentage of total model runs in which the NPV is negative. Gain indicates the percentage of results with positive NPV.

Table A-3*: Distribution of Net Present Value (NPV) based on 10,000 Monte Carlo model runs for all the stakeholders, the implementer, the environment, and total project outcome for the implementation of an irrigation dam project, without catchment restoration in Tigray, Ethiopia*

Description	Distribution of simulation outcome (Million USD)			Chance (%)	
	5%	50%	95%	loss	Gain
Environment	-0.31	-0.21	-0.14	100	0
Downstream irrigators	1.25	3.35	5.74	2.42	97.58
Displaced irrigators	-0.5	0.34	0.95	23.51	76.49
Upstream non-irrigators	0.14	0.29	0.52	0	100
Downstream non-irrigators	-0.28	0.06	0.21	32.57	67.43
Implementer	-17.25	-13.29	-10.76	100	0
Total project effect	**-14.56**	**-9.53**	**-5.72**	**100**	**0**

Note: the chance of loss is the percentage of total model runs in which the NPV is negative. Gain indicates the percentage of results with positive NPV.

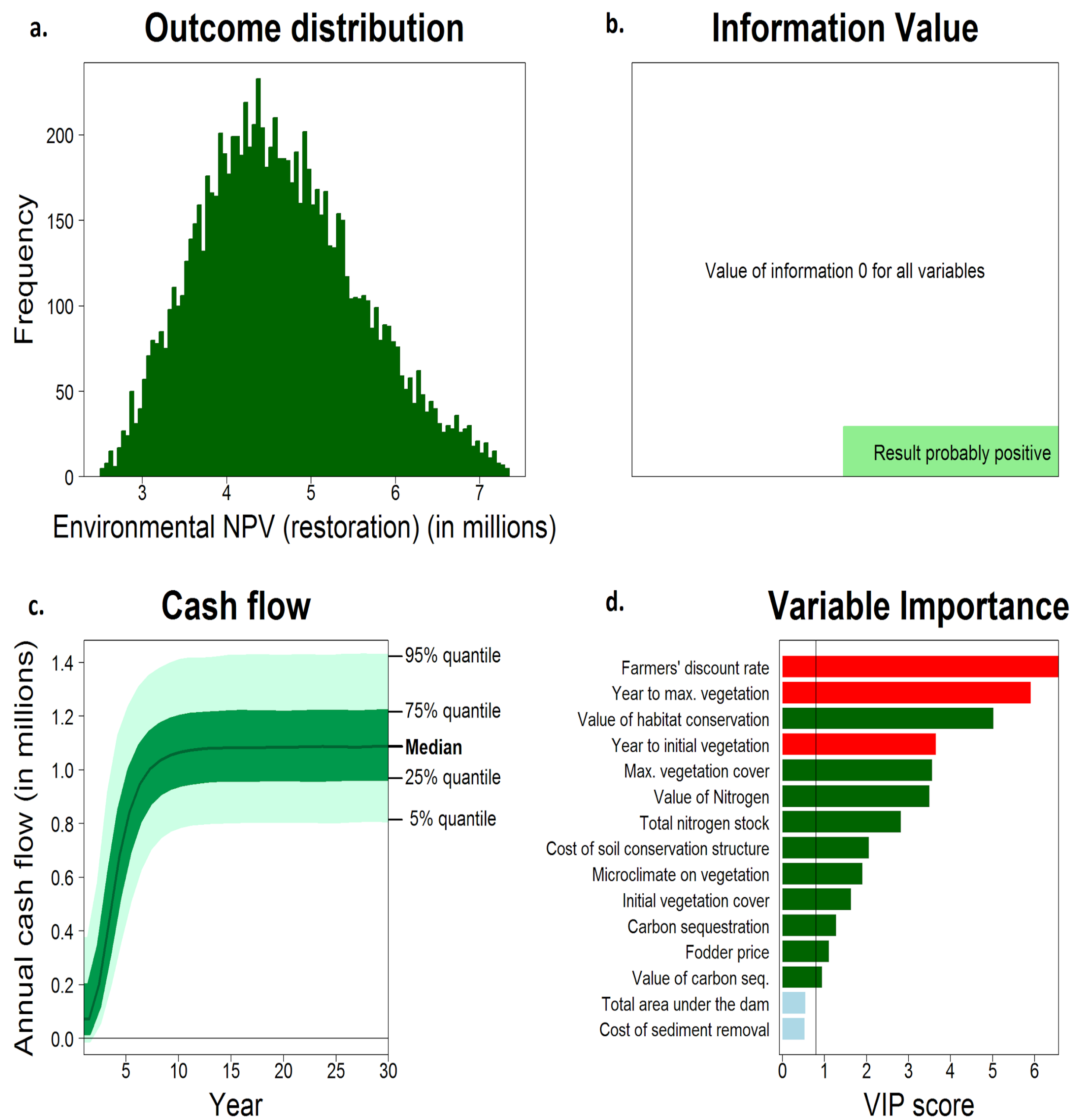

Figure A-1: Simulation results from 10,000 model runs for the **environmental effects** of implementing an irrigation dam**, with catchment restoration**, in Tigray, Ethiopia.

a. *distribution of project outcome expressed as the Net Present Value (NPV), positive (green) and negative (red).* ***b.*** *Expected Value of Perfect Information (EVPI). EVPI>0 indicates that the selected uncertain variable has information value and further measurement is recommended to reduce model uncertainty.* ***c.*** *distribution of modeled annual net cashflow over the expected project life span of 30 years.* ***d.*** *variable importance in the projection (VIP) highlighting all* *model variables with a VIP greater than 0.8 (black vertical line) and correlation with project outcome, positive (green) and negative (red).*

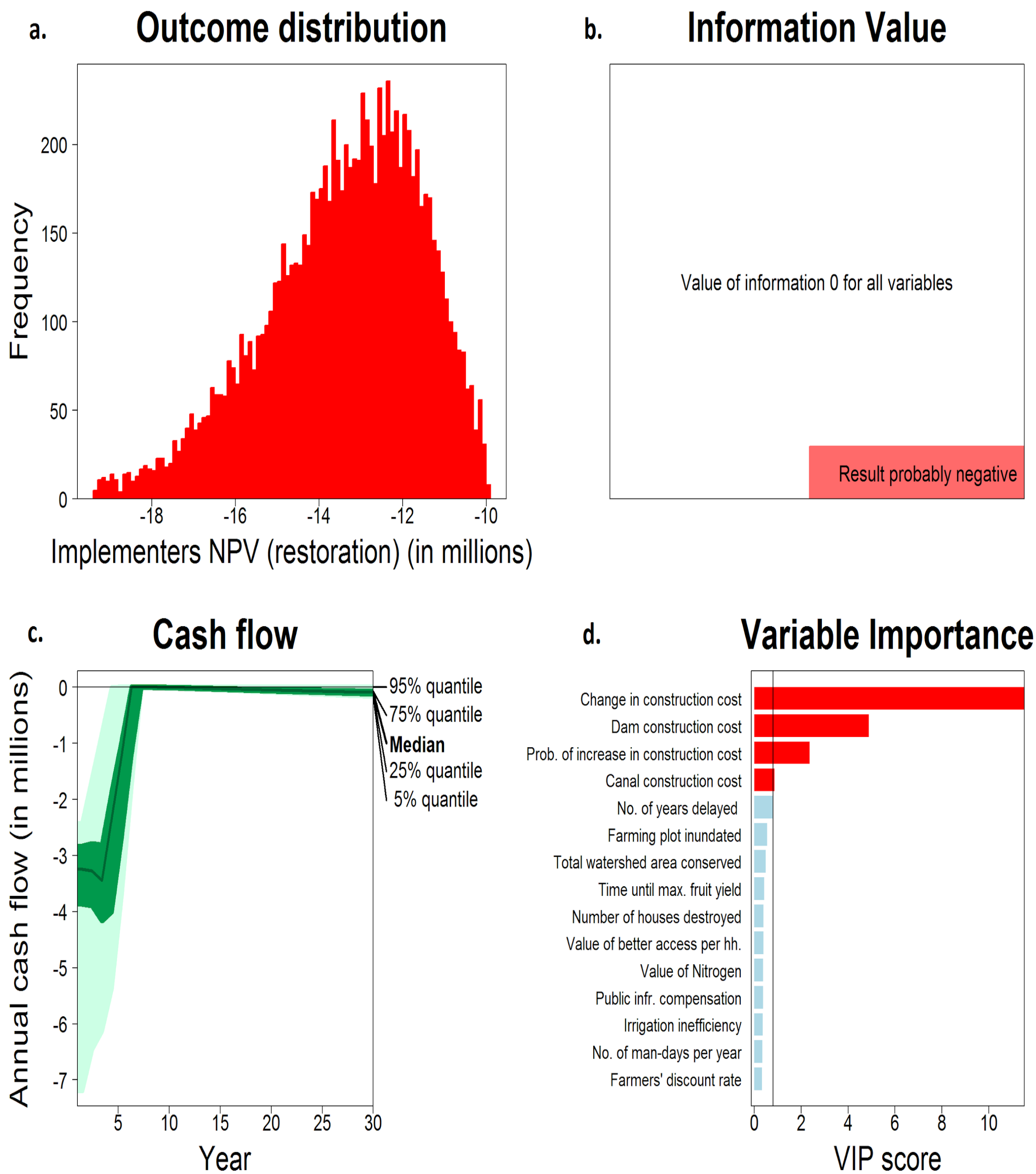

Figure A-2: Simulation results from 10,000 model runs for the **implementer** for the implementation of a proposed irrigation dam, **with catchment restoration**, in Tigray, Ethiopia.

*For detailed description of the graphs and bars, see legend to **Figure A-1***

Table A-4: List of parameters identified by the experts for an irrigation dam construction, their corresponding estimates, and distribution type

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Expected life of the dam (i.e. simulation period)	30	30	const
Coefficient of variation introduced for water allocation	10	20	posnorm
General coefficient of variation	5	10	posnorm
Farmers discount rate	15	20	posnorm
Discount rate (Implementer)	10	10	const
Construction duration (years)	2	2	const
Water holding capacity of the dam	4,500,000	6,500,000	posnorm
Water loss due to evaporation (as percentage of the dam water holding capacity)	4	8	posnorm
Water percolate into the ground (as percentage of the dam's water holding capacity)	0.5	1	posnorm
Water loss due to seepage (as percentage of the dam's water holding capacity)	0.3	1	posnorm
Crop water requirement	4,500	7,000	posnorm
Loss of water due to irrigation inefficiency	0.4	0.6	posnorm
Maximum area suitable for irrigation (i.e. area that has an irrigation structure)	350	405	posnorm
Years without fruit production after plantation	4	7	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Time from planting until maximum fruit yield (years)	10	15	posnorm
Fruit (mango, orange...) initial productivity per hectare (ton)	3	6	posnorm
Maximum attainable fruit yield	10	16	posnorm
Proportion of area for fruit production	0.15	0.3	tnorm_0_1
Fruit price per ton	10000	20000	posnorm
Time to reach a maximum crop harvest (years)	5	10	posnorm
Initial vegetable (onion and tomato) productivity per hectare (ton)	12	15	posnorm
Maximum attainable vegetable productivity	18	24	posnorm
Vegetable price per ton	7000	10000	posnorm
Initial groundnut productivity per hectare (ton)	0.5	1.4	posnorm
Maximum attainable groundnut productivity	1.6	3	posnorm
Proportion of area for groundnut production	0.01	0.05	tnorm_0_1
Groundnut price per ton	6500	8000	posnorm
Initial maize productivity per hectare (ton)	1.5	3	posnorm
Maximum attainable maize productivity	3.5	5	posnorm
Proportion of area for maize production	0.05	0.1	tnorm_0_1
Maize price per ton	5000	6500	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Area shared for the displaced upstream villagers	40	60	posnorm
Proportion of supplementary irrigators further downstream	0.5	0.9	posnorm
Probability of dry spell	0.2	0.6	tnorm_0_1
Per hectare water requirement for supplementary irrigation	2000	3500	posnorm
Share of irrigable area that gets supplementary irrigation during dry spell	0.3	0.8	posnorm
Wet season yield when sufficient water is available	2	5	norm
Yield reduction by dry spell during the wet season	0.2	0.9	tnorm_0_1
crop price for crops produced during rainy season (i.e. under rain fed or supplementary)	8000	15000	norm
Additional cost incurred due to supplementary irrigation per hectare	500	2000	posnorm
Probability of flood water used for supplement	0.4	0.7	tnorm_0_1
Prevention of percentage of yield reduction through flooding	0.5	0.8	tnorm_0_1
Probability of rainfed supplement through irrigation	0.8	0.9	tnorm_0_1
Prevention of percentage of yield reduction through irrigation	0.7	0.95	tnorm_0_1
Agricultural area further downstream	300	700	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Expected value forgone by retaining the alluvial deposits (ETB/km2)	1000	3000	posnorm
Per hectare orchard establishment cost	50000	80000	posnorm
Per hectare maximum fruit production cost	30000	50000	posnorm
Cost of fruit production per hectare after year one	10000	20000	posnorm
Per hectare vegetable input, harvesting and transportation cost	25000	40000	posnorm
Per hectare groundnut input, harvesting and transportation cost	5000	10000	posnorm
Per hectare fruit maize, harvesting and transportation cost	5000	10000	posnorm
Per hectare production cost	5000	10000	posnorm
Probability of water supply	0.5	0.8	tnorm_0_1
Current population	23000	26000	posnorm
Annual population growth rate	2	5	posnorm
Current percentage water coverage	50	60	posnorm
Annual planned increment in the rate of coverage	0.5	3	posnorm
Planned water consumption (liters per capita demand)	40	60	posnorm
Water demand from commercial, public institutions and industries (as percentage of total public water demand)	10	30	posnorm
Current water pumping capacity per hour in m3	150	180	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Total number of operational hours per day	8	12	posnorm
Number of days operating in a year	300	350	posnorm
Number of days of labor per year	35000	50000	posnorm
Cost of labour (birr per work-days)	70	100	posnorm
Employment income as percentage of other activities(watershed practices and repair and maintenance budget)	0.05	0.1	posnorm
Household labour cost	40	60	posnorm
Number of days of labor of job opportunity created per hectare	100	400	posnorm
Proportion of employees who are from upstream villages and live in the upper catchment	0.2	0.35	posnorm
Proportion of employees who are displaced from the upstream	0.1	0.15	posnorm
Proportion of employee from further downstream	0.1	0.25	posnorm
Number of households consuming water from the dam	50	300	posnorm
Proportion of households who have livestock that drink from the dam	0.2	0.6	posnorm
Average number of TLU per household	1	3	posnorm
Annual per household rural water consumption	10	35	posnorm
Annual per livestock water consumption	3	8	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Probability of the dam water used for rural household consumption	0.3	0.7	tnorm_0_1
Probability of the dam water used for livestock consumption	0.6	0.8	tnorm_0_1
Total annual time saved by fetching water from the dam (per each household)	40	90	posnorm
Total annual time saved by watering livestock from the dam (per each household)	10	40	posnorm
Percentage increased in vegetation cover due to improve in microclimate of the area (as % of expected vegetation growth rate in the area)	5	15	posnorm
Percentage increase in yield due to improve in microclimate	5	10	posnorm
Maximum attainable vegetation cover (as percentage of total area intervened)	75	90	posnorm
Initially realized vegetation cover (as percentage of maximum vegetable cover)	5	15	posnorm
Number of years to first increase in vegetation cover	1	2	posnorm
Number of years to maximum vegetation cover	5	20	posnorm
Increase in vegetation cover around the dam (km2)	0.02	0.05	posnorm
Proportion of catchment area suitable for fodder production, including the area	30	50	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
around the reservoir (as percentage of total catchment area intervened)			
Expected maximum fodder production (ton/km2)	250	300	posnorm
Expected value (price) of the fodder (ETB/ton)	500	1000	posnorm
Probability of harvesting fuelwood from the restored area	0.05	0.5	posnorm
Expected maximum harvested fuelwood (ton/km2)	70	120	posnorm
Expected value (price) of the fuelwood (ETB/ton)	500	1000	posnorm
Probability of collecting medicinal material from the restored catchment area	0.01	0.2	posnorm
The expected value of medicinal plant collected (ETB/km2)	1500	20000	posnorm
Proportion of area susceptible for erosion	50	70	posnorm
Maximum expected annual increase in soil nitrogen content (Mg TN/km2)	50	70	posnorm
Expected value of total soil nitrogen (ETB/Mg TN)	6000	9000	posnorm
Maximum expected change in available phosphorus stock (Mg AP/km2)	0.2	0.5	posnorm
Expected value of annual increase in available phosphorus stock (ETB/Mg AP)	12000	14000	posnorm

Descriptions	**Estimate (90% CI)**		**Distribution**
	Lower bound	**Upper bound**	
Maximum annual carbon sequestration potential of the vegetation area (Mg Co2/km2)	1800	2400	posnorm
Value of carbon sequestration (ETB/Mg Co2)	90	110	posnorm
The expected value of habitat conservation under maximum vegetative cover (ETB/km2)	50000	300000	posnorm
The expected cultural value attached to the restored catchment	20000	100000	posnorm
The expected cultural value attached to the reservoir	1000	5000	posnorm
Dam construction cost	2.18E+08	2.65E+08	posnorm
Primary and secondary canal construction cost	49100000	59300000	posnorm
Supervision and monitoring cost	810000	880000	posnorm
Study and design cost	100000	200000	posnorm
Cost of soil conservation structure per km^2	40000	230000	posnorm
Total watershed (catchment) area that needs restoration (km^2)	32.24	32.24	const
Total watershed (catchment) area (km^2)	10	20	posnorm
Proportion construction completed in year 1	50	60	posnorm
Proportion construction completed in year 2	20	30	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Cost of guards for area closure (i.e. annual salary of 5 persons with individual monthly salary of 1000-2000 and half of it is going to be covered by the community)	30,000	60,000	posnorm
Cost of forest seedling per km^2	5,000	10,000	posnorm
Cost of planting and management per km^2	5,000	10,000	posnorm
Farming plot inundated by the dam (hectare)	45	60	posnorm
Annual compensation per hectare	45,000	65,000	posnorm
Total number of houses to be destroyed	45	55	posnorm
Annual compensation per house	15,000	22,000	posnorm
Total public infrastructure lost (school)	1	1	const
Compensation for constructing the public infrastructure	1,200,000	1,800,000	posnorm
Proportion of repair and maintenance cost to dam construction cost	5	10	posnorm
Annual value of having a better access per household	400	500	posnorm
Annual expense to get the better access	100	200	posnorm
Resettlement duration	1	3	posnorm
Cost of constructing house in the study area	15,000	30,000	posnorm
Social and cultural cost of displacement	5,000	100,000	posnorm
Probability of flood eroded land	0.1	0.4	tnorm_0_1
The value of controlled erosion	5,000	100,000	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Probability of a house destroyed by flood	0.05	0.2	tnorm_0_1
Number of houses destroyed	1	10	posnorm
Probability of flood washed away human beings	0.001	0.01	tnorm_0_1
Value of human life	40,000	100,000	posnorm
Number of people washed away by flood	1	3	posnorm
Probability of flood washed away livestock	0.05	0.2	tnorm_0_1
Value of each livestock	500	4,000	posnorm
Number of livestock washed away by flood	2	20	posnorm
Proportion of downstream irrigators affected by flooding	0.1	0.4	tnorm_0_1
Expected reduction in vegetation area below the reservoir (km2) with restoration	0.05	0.3	posnorm
Expected reduction in vegetation area below the reservoir (km2) without restoration	0.04	0.25	posnorm
Total area under the dam in km2	0.5	1	posnorm
probability of dam failure	0.005	0.01	posnorm
cost of dam failure sharing in the upstream displaced	0.1	0.2	posnorm
cost of dam failure sharing in the further downstream	0.15	0.3	posnorm
Cost of dam failure	10,000,000	25,000,000	posnorm
probability of rainfall fluctuation (drop)	0.15	0.25	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Volume of water reduced from the reservoir due to rainfall drop (m^3)	120,000	2,000,000	posnorm
probability of increasing construction cost	0.7	0.9	tnorm_0_1
percentage increase in construction cost	5	25	posnorm
probability of decline in output price	0.1	0.3	posnorm
percentage change in output price	5	10	posnorm
Probability of practicing water trap in upstream area	0.15	0.2	posnorm
Volume of water reduced from the reservoir due to water diversion practice (m3)	180000	500000	posnorm
Probability of Malaria outbreak	0.3	0.5	posnorm
Total cost due to malaria out break	200000	1000000	posnorm
Probability of delay in construction timing	0.75	0.9	tnorm_0_1
Duration of delay	2	3	posnorm
Probability of sedimentation beyond the expected maximum threshold (i.e. expected every five or 10 years)	0.1	0.2	posnorm
Value of removing accumulated sediment	3000000	8000000	posnorm
Ethiopian birr (ETB) to US dollar exchange rate	27.0843	27.0843	const
Calories from fruits	362874	544311	posnorm
Vitamin-A from fruits	69251	103876	posnorm
Calories from vegetable	181437	272156	posnorm
Vitamin-A from vegetable	3527953	5039933	posnorm

Descriptions	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Calories from groundnut	4082351	6350323	posnorm
Vitamin-A from groundnut	0	0	const
Calories from maize	1814382	3719483	posnorm
Vitamin-A from maize	58909	141381	posnorm
Calories from other crops	1814386	3628772	posnorm
Vitamin-A from other crops	94254	141381	posnorm
Daily calorie requirement	1200	3500	posnorm
Daily vitamin A requirement	650	950	posnorm
Postharvest losses	10	60	posnorm

Distribution type: posnorm is positive normal distribution, const is constant and tnorm_0_1 is truncated normal distribution between the value of zero and one.

Table A-5: ***List of parameters identified by the experts for a road-water harvesting intervention in Tigray region of Ethiopia, their corresponding estimates, and the distribution types***

Description	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Expected life of the water harvesting structures (years)	10	10	const
Coefficient of variation for water allocation	10	20	posnorm
General coefficient of Variation	5	10	posnorm
Farmers discount rate	15	20	posnorm
Discount rate	10	10	const
Exchange rate	27	27	const
Volume of water in one kilometer (m^3)	50,000	75,000	posnorm
Water holding capacity of farm ponds (m^3)	400	500	norm
Water holding capacity of a check dam (m^3)	750	1000	norm
Water holding capacity of percolation pond (m^3)	400	500	norm
Percentage of water loss from percolation pond	5	10	posnorm
Percentage of water loss from farm pond and check dam	25	50	posnorm
Probability of the water using for home and livestock consumption	0.4	0.5	tnorm_0_1
Per capita water consumption (m^3/year)	10	20	posnorm
Proportion of households who have livestock that consumes water from the dam	0.2	0.6	posnorm
Average number of TLU per household	1	3	posnorm
Annual water consumption per TLU (m^3/TLU/year)	20	40	posnorm
Water tariff for domestic and livestock consumption (Birr/m^3)	5	10	posnorm
Per hectare water requirement for supplementing (m^3/ha)	2,000	3,000	posnorm
Per hectare water requirement for irrigation (m^3/ha)	8,000	13,000	posnorm

Description	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Probability of reduction in rainfall	0.05	0.1	norm
Reduction in volume of water harvested due to reduction in rainfall (%)	20	30	norm
Revenue from irrigation per hectare (ETB)	80,000	100,000	posnorm
Net gain from rain-fed system under baseline scenario (ETB/ hectare)	30,000	40,000	posnorm
Supplementing benefit as percentage of rain-fed revenue	60	80	posnorm
Employment income from construction of the structure (as percentage of total construction cost)	5	10	posnorm
Farm employment income (as percentage of total farm operational cost)	10	30	posnorm
Repair and Maintenance job opportunity (as percentage of total repair and maintenance cost)	2	5	posnorm
Frequency of filling the percolation structure per year	3	5	norm
Probability of flooding	0.8	0.9	tnorm_0_1
Probability of flood that affect farming plot	0.05	0.1	tnorm_0_1
Area of farming plot in 1km road (ha)	1	5	posnorm
Percentage of farming plot damaged	1	10	posnorm
Probability of flood that affect settlement	0.05	0.1	tnorm_0_1
Total settlements per 1km road	5	10	posnorm
Percentage settlements damaged (%)	1	3	posnorm
Value of the settlement destroyed (ETB)	15,000	30,000	posnorm
Probability of detour in the road	0.01	0.05	tnorm_0_1
Detour cost (ETB)	10,000	50,000	posnorm
Probability of damaging other household asset	0.01	0.05	tnorm_0_1
Value of the household asset destroyed (ETB)	15,000	50,000	posnorm
Probability of gully formation	0.3	0.5	tnorm_0_1

Description	**Estimate (90% CI)**		**Distribution**
	Lower bound	**Upper bound**	
Annual cost of the gulley formed (ETB)	10,000	20,000	posnorm
Road maintenance cost per 1km road	100,000	150,000	posnorm
Proportion maintenance cost saved due to water harvesting (%)	50	60	posnorm
Value of improvement in micro-climate (Birr/km)	10,000	20,000	posnorm
Area suitable for vegetative cover in ha	10	20	posnorm
Percentage of the area covered per year	10	20	posnorm
Value of vegetative cover per hectare (ETB)	10,000	20,000	posnorm
Number of participant	5	20	posnorm
Cost per participant (ETB)	1,500	3,000	posnorm
Farm pond construction cost (ETB)	8,000	10,000	norm
Check dam construction cost (ETB)	40,000	70,000	norm
Percolation pond construction cost	10,000	15,000	norm
Study and design of road water harvesting structure (Birr/km)	5,000	10,000	posnorm
Percentage of cost for monitoring and supervision of road water harvesting structure (% of construction cost)	2	5	posnorm
Repair and management cost (% of total construction cost)	5	10	posnorm
Additional cost of constructing road drainage system (ETB/Km2)	20,000	30,000	posnorm
Total no of people buying water treatment and mesquite repellent nets with in a km road	15	30	posnorm
Cost of public health protection (Birr/person)	200	500	posnorm
Farm operational cost (Birr/ha)	10,000	15,000	posnorm
Additional cost incurred due to supplementary irrigation per hectare	1,000	2,000	posnorm
Farm plot under a single pond in hectare (i.e. this is computed the volume of water divided by the deepness of the structure, which is 5 meter)	0.006	0.01	posnorm
Probability of water logging	0.1	0.3	tnorm_0_1

Description	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Area affected by water logging (ha)	0.01	0.5	posnorm
Cost of land reclamation due to water logging (ETB/ha)	1,000	3,000	posnorm
Probability of improper design and implementation that leads to total demolition of the structure	0.01	0.05	tnorm_0_1
Probability of structural and/or hydraulic damage	0.05	0.1	tnorm_0_1
Additional cost due to structural and hydraulic damage (ETB)	1,000	5,000	posnorm
Probability of siltation	0.01	0.05	tnorm_0_1
Percentage of annual volume of water reduced from the structure due to sedimentation (m^3/year)	5	10	norm
Probability of malaria infestation or spread	0.01	0.05	tnorm_0_1
Number of persons affected	5	20	posnorm
Total cost per person (both treatment and income foregone) (ETB)	1,000	3,000	posnorm
Probability of water pollution	0.01	0.03	tnorm_0_1
Probability of oil and fuel spills	0.01	0.05	tnorm_0_1
Total number of people affected due to pollution	5	20	posnorm
Treatment cost per person from pollution (ETB)	200	1,000	posnorm
Land reclamation cost due to pollution (ETB)	5,000	10,000	posnorm

Distribution type: posnorm is positive normal distribution, const is constant and tnorm_0_1 is truncated normal distribution between the value of zero and one.

Table A-6: List of parameters identified by the experts for a spate irrigation intervention in Turkana county Kenya, their corresponding estimates and distribution type

Description of input parameter	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Number of years to run the simulation	25	25	const
General coefficient of Variation	5	10	posnorm
Farmers discount rate	15	20	posnorm
Discount rate	10	10	const
Amount of additional pasture from the proposed intervention (Tons/ha)	2	10	posnorm
Total area under the mini project (ha)	50	100	posnorm
Total area under mega system (ha)	101	200	posnorm
Price of the pasture (KSh/Ton)	20,000	50,000	posnorm
Reduced trickling distance of pastoralists (km/year)	400	1,000	posnorm
Distance covered per hour under the current situation (km/hr)	0.5	1	posnorm
Per hectare number of pastoralist in the system	3	5	posnorm
Value of the time saved (KSh/hr)	8	10	posnorm
Expected increase in weight (kg/TLU)	20	50	posnorm
Expected increase of milk (lt/TLU)	600	900	posnorm
Additional carrying capacity (TLU/ha)	1	3	posnorm
Proportion of dairy TLU	0.1	0.4	tnorm_0_1
Price of the body weight gain (KSh/kg)	200	400	posnorm
Price of milk (KSh /lt)	50	100	posnorm
Total number of population in the area	1500	3,000	posnorm
Proportion of population getting training	0.1	0.2	tnorm_0_1
Proportion of trained who adopt	0.4	0.6	tnorm_0_1
Value of the capacity development (KSh/person)	20,000	50,000	posnorm
Additional production (Ton/ha)	0.9	1.8	norm
Prop crop area under mixed system	0.7	0.9	tnorm_0_1
Price of produce (KSh/Ton)	80,000	100,000	posnorm
Increase in residue (Ton/ha)	2.7	5.4	norm
Price of residue (KSh /Ton)	20,000	50,000	posnorm
Annual Man-days farm job created (man-day/ha)	60	150	posnorm
Annual Man-days off farm job created under mini	500	2,500	posnorm

Description of input parameter	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Annual Man-days off farm job created under mega	1,000	5,000	posnorm
Percent of Man-day of construction job created (% of total project cost)	1	5	posnorm
Number of Man-day of watershed management job created per km^2	30	50	posnorm
Family labor cost	100	300	posnorm
Off-farm labor cost	400	600	posnorm
The value of reduction in flooding effect under mini project	1,000,000	2,000,000	posnorm
The value of reduction in flooding effect under mega project	2,700,000	4,500,000	posnorm
Value of improvement in ecosystem and microclimate per km^2	200,000	300,000	posnorm
Cover density per square kilometer	0.1	0.2	tnorm_0_1
Total watershed area (as multipler of total command area)	3	3	const
Value of additional cover (KSh /km^2)	200,000	300,000	posnorm
Annual percentage of area reclaimed (%/100)	10	20	posnorm
Value of reclaimed area	625,000	900,000	posnorm
Input cost per ha	5,000	10,000	posnorm
Individual labor contribution under mega(Man-days/yr)	100	150	posnorm
Individual labor contribution under mini (Man-days/yr)	50	75	posnorm
Perimeter fenced under mega (km)	4	20	posnorm
Perimeter fenced under mini (km)	1	4	posnorm
Cost per km for fencing	100,000	300,000	posnorm
Value of trees cleared for one km of perimeter fencing	10,000	30,000	posnorm
Area exposed to soil disturbance and emission (%)	10	20	posnorm
Value of the soil disturbance per ha	1,000	5,000	posnorm
Total number of area reduced under mega (ha)	5	10	posnorm
Total number of area reduced under mini	1	5	posnorm
Area benefiting from alluvial deposits under mega(ha)	5	10	posnorm

Description of input parameter	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
Area benefiting from alluvial deposits under mini (ha)	1	5	posnorm
Value of alluvial deposits per ha	1,000	2,000	posnorm
Cases reported/total no people affected under mega	10	30	posnorm
Cases reported/total no people affected under mini	1	10	posnorm
Cost of health treatment per person per year	400	500	posnorm
Proportion of area to be converted from pasture land to crop farming (% /100 of total crop area)	0.5	0.9	tnorm_0_1
Value of pasture under current condition	20,000	30,000	posnorm
Clearing costs per ha for crop producers	100,000	200,000	posnorm
Cost of study and design for mega	600,000	2,000,000	posnorm
Cost of study and design for mini	200,000	600000	posnorm
Total cost of training/community brazes under mini	700,000	900,000	posnorm
Total cost of training/community brazes under mega	1,500,000	2,000,000	posnorm
Construction cost of the structure for mega (KSh/ha)	150,000	750,000	posnorm
Construction cost of the structure for mini (KSh/ha)	75,000	300,000	posnorm
Percentage area to be intervened	30	50	posnorm
Cost for watershed management per km^2	2,000,000	5,000,000	posnorm
Repair and maintenance cost as a percentage of total investment	5	15	posnorm
Probability of having sloppy area	0.2	0.4	tnorm_0_1
Cost of the slope as a percentage of infrastructure cost	20	50	posnorm
Probability of improper design and planning	0.002	0.004	tnorm_0_1
Probability of accurate supervision	0.8	0.9	tnorm_0_1
Probability of rejecting supervisors suggestion	0.004	0.02	tnorm_0_1
Additional cost of supervision as proportion of total project cost	0.03	0.06	tnorm_0_1
Probability of total structural failure (if there is design problem or improper	0.3	0.8	tnorm_0_1

Description of input parameter	Estimate (90% CI)		Distribution
	Lower bound	Upper bound	
interpretation and construction of the structure)			
Probability of occurrence of conflict	0.2	0.3	tnorm_0_1
Cost of managing conflict	20,000	100,000	posnorm
Probability of siltation	0.8	0.9	tnorm_0_1
Probability of below expected rainfall	0.2	0.4	tnorm_0_1
Percentage reduction in crop yields	40	70	posnorm
Percentage reduction in pastures	50	60	posnorm
Probable occurrence excessive rainfall (annual)	0.01	0.1	tnorm_0_1
Probability of flooding farming plot	0.04	0.1	tnorm_0_1
Percentage reduction of crop yield (%/100)	50	80	posnorm
Dollar to KSh exchange rate as of 05 June, 2018	100	100	const

Distribution type: posnorm is positive normal distribution, const is constant and tnorm_0_1 is truncated normal distribution between the value of zero and one.