DYNAMICS OF WATER-MANAGEMENT SYSTEMS IN HISTORICAL EAST AFRICAN AGRICULTURAL SOCIETIES: MODELLING THE LONG-TERM ECOSYSTEM AND SOCIOECONOMIC INTERACTIONS IN A HISTORICAL AGRONOMY IN ENGARUKA, TANZANIA

Tabitha Kemunto Kabora

PhD

University of York

Archaeology

June 2018

Abstract

The research conducted explored the dynamics of the historical water-management system that was in use at Engaruka, Tanzania, between the 15th to 18th centuries CE, the aim being to model the primary human and environmental factors and their interactions, and to assess how these influenced the development of the system at several spatial and temporal scales. To achieve this overarching aim, the research utilised archaeological evidence, agent-based modelling techniques, analysis of hydrodynamics, DEM data and palaeoclimatic data analysis. In order to create simplified reconstructions of the Engaruka system, two agent-based models were developed that incorporate archaeological evidence, hydrological data, topographical data, qualitative data and palaeoecological data at different spatial and temporal scales. The ESTRaP model demonstrates that sediments accumulation within a 6 × 6 m field can take place in the relatively short period of a single season, which could be managed by a small number of farmer households constructing blocks of fields concurrently across the landscape; leading to the complex network of irrigated fields at Engaruka. The TIME-MACHINE model demonstrates that there was not necessarily a catastrophic climatic or environmental event that accounts for the abandonment of the historical Engaruka system, but rather a combination of environmental and social factors could have influenced the farmer households into giving up agriculture for alternative subsistence activities on a household to household basis. The ABMs developed in this research represent first steps in the integration of archaeological evidence with ABM techniques in order to understand the Engaruka site. This research shows how the integration of data from different sources and disciplines can help in our understanding of how the system could have developed by integrating a multitude of factors and showing how these interactions influenced the development of the system.

List of Contents

List of Figures

List of Tables

List of Accompanying Material

Folder 01 Model Analysis and Outputs

1. ESTRaP Sensitivity Analysis
2. TIME-MACHINE Sensitivity Analysis-Environment
3. TIME-MACHINE Sensitivity Analysis-Human
4. ESTRaP Scenario Results
5. TIME-MACHINE Scenario Results

Folder 02 ESTRaP model

1. ESTRaP ABM model
2. ESTRaP ABM setup guide

Folder 03 TIME-MACHINE model

1. TIME-MACHINE ABM model
2. TIME-MACHINE setup guide

Acknowledgements

This research formed part of the Archaeology of Agricultural Resilience in Eastern Africa (AAREA) project which was funded by the European Research Council under the European Union's Seventh Framework Programme Starter Grant Scheme (FP/200702013/ERC); Grant Agreement No. ERC-StG-2012-337128-AAREA awarded to Dr Daryl Stump. The Aerial Surveys conducted under this research were funded by The British Institute in East Africa Thematic Grants 2015, and the Department of Archaeology, University of York.

Sincere thanks to my supervisors Dr Daryl Stump at the University of York and Professor John Wainwright at Durham University for their guidance, critique and invaluable support. I would like to thank Dr Stump for his expertise in archaeological research and the opportunities provided to conduct this research under the AAREA project. Special thanks for introducing me to the "Diversity Cupboard" and "Carruthers". I would like to thank Prof Wainwright for sharing his expertise in hydrological, ecological and geomorphic processes, and modelling human-environment interactions, and for providing the opportunity to collaborate in this exciting research. Special thanks for reminding me that Resistance is Futile. I would like to acknowledge the support of the AAREA project advisors who contributed their time and expertise to this research. I am also grateful to Mr Steve Roskams whose support as chair of my Thesis Advisory Panel, helped shape the course of my work.

I would like to thank members of the AAREA project team who provided support and advice, and contributed time and expertise that honed my research skills and shaped the course of this research. Sincere thanks to Dr Carol Lang, Dr Cruz Ferro-Vasquez, Dr Suzi Richer and Senna Thornton-Barnett as well as Dr Gianni Gallello; we began under the AAREA project as colleagues and finished as friends. Special thanks to my closest friends and fellow PhD candidates: Andriannah Mbandi, Manogna Goparaju, Melony Bethala, Jamie Khoo and Esther Githumbi for their support and the endless supplies of cake and tea.

Finally, to my parents James and Margaret Kabora, and siblings Aaron, Willis and Michael; your support and encouragement sustained me through it all.

Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Chapter 1 Introduction and Literature Review

1.1 Introduction

The study of water management systems in Africa and in particular eastern Africa has been limited in previous academic research. However, the importance of understanding how these systems function, especially in the arid and semi-arid lands, in order to provide sound evidence to support development interventions means more attention needs to be paid to the socioeconomic and environmental factors that influence the functioning of both historical and contemporary water management systems. While numerous studies have been conducted on historical water management systems, few have been conducted in the east African region with a specific view of understanding the factors that influenced their development. In addition, many of these studies have looked at singular factors that influenced the development of these systems with some focusing on the human factors while others focus on the environmental factors, for example the environmental impacts of these systems or the social factors that influenced the development of irrigation and agricultural terracing practices (Stump 2010a; Widgren 2010; Harrower 2008; Costanza *et al.* 2007). The factors that influence the development of water management systems vary across regions and over time and different factors can exert influence on these systems to varying degrees both spatially and temporally. The problem that this research intends to address is to determine the primary human and environmental factors and their interactions that influence the development of a historical water management system in eastern Africa, over a temporal and spatial scale.

The debates surrounding various water management systems and how they develop and are maintained tie to three main concepts: longevity, resilience and sustainability. Longevity describes the length of time a system exists in a given state, while ecological resilience is the ability of a system to recover after a disturbance or perturbation and retain its structure, functions and feedbacks, while sustainability, in contrast is defined as the capacity of a system to maintain its structure, diversity and productivity for an indefinite period of time (Gunderson 2000; Costanza and Patten 1995). These three concepts play a role in development debates where archaeological and ethnographic evidence of historical agronomies are interpreted to support different arguments on sustainability where, in some cases, longevity has been considered a sign of sustainability and resilience.

However, these interpretations do not take into consideration the interaction of human and environmental factors and the assessment of long term sustainable management in these historical systems remains vaguely understood.

There are multiple possible human and environmental factors that can influence the development of the complex historical agronomies such as those found in Engaruka, Tanzania and Konso, Ethiopia; such as human factors of population growth, labour and trade as well as environmental factors of topography, hydrology and climate. In addition, these factors interact in various degrees and with varying influence resulting in an infinite number of scenarios for how and why a system developed. In order to understand how these systems work would require massive data sets and extensive studies on the different factors and their interactions. However limitations on the available data and difficulties in assessing which are the primary factors over time and space and their interaction would result in an incomplete picture. Agent based models represent an alternative tool that allows the assessment of the different socioeconomic and environmental factors and their interactions by taking the available data, designing a simplified version of the system and constructing simulations of the possible scenarios that would influence the establishment, development and maintenance of the historical agronomies.

In this research, agent-based models (ABMs) were developed that incorporate the archaeological evidence, hydrological data, topographical data, qualitative data and palaeoecological data to create a simplified reconstruction of the Engaruka system. These models were used to assess the dynamics of the historical system where the environmental and human factors can be analysed and interrelated over a spatial and temporal scale across multiple scenarios. By representing the dynamic human-environment interactions and the key feedbacks, the study can thus represent and assess the reciprocal impacts of human activity on natural systems.

1.1.1 Research Aims

The aim of the research being undertaken is:

- To model the primary human and environmental factors and their interactions that influence the development of the historical Engaruka water-management system in east Africa, over a temporal and spatial scale.

To achieve this overarching aim, the research utilised archaeological evidence, agent-based modelling techniques, analysis of hydrodynamics, DEM data and palaeoclimatic data analysis to answer three questions:

1. To what extent does the incorporation of irrigation canals and sediment trap fields influence the hydrological and sedimentary processes across the landscape and the irrigation system over time?
2. To what extent does the modification of water movement influence crop production and crop yields within the system?
3. To what extent does the interaction of environmental and social factors influence the development and continued use of the Engaruka field system?

The agent-based models developed under this research are intended to advance our understanding of the environmental and socioeconomic factors that influenced the development and expansion of the historical Engaruka water-management system. The research develops replicable techniques that combine archaeological evidence with agent-based modelling in order to meet the research aim as well as providing techniques for the assessment of other similar historical systems. The research conducted forms part of the Archaeology of Agricultural Resilience in Eastern Africa (AAREA) project whereby the research of other project members provided data and concepts that were incorporated into the ABMs developed. The research from other project members included archaeological data from stratigraphic excavations and GIS surveys, interpretations of soil micromorphology and dating data, and archaeobotanical interpretations. This was incorporated into the agent-based modelling work along with the extensive sedimentological and hydrological research conducted as part of this doctoral research. This research therefore presents a substantial and original contribution through the use of agent-based modelling and different data sources from a wide range of scientific disciplines, in combination with behavioural rules generated from modern datasets and analogous systems, to generate new knowledge on the development of the historical Engaruka system.

1.1.2 Thesis Layout

The thesis is divided into six chapters: Introduction and literature review, Methodology and results, Model conceptualisation, ESTRaP model, TIME-MACHINE model, and Synthesis and conclusions.

The remainder of this chapter, which forms part of **Chapter One**, provides a background to the existing literature on historical water-management systems and discusses some of the environmental and social factors that could influence their development. The literature on modelling of water management systems and the existing gaps in are also discussed. The aims of the research, as well as the research questions to be explored are then outlined further.

Chapter Two outlines the field studies conducted, the methodology employed in data collection and the results obtained. The study areas of Engaruka, Tanzania and Konso, Ethiopia are outlined and the rationale for their selection is explained. The methods employed include archaeological excavations, topographic surveys, aerial surveys, hydrologic surveys and semi-structured interviews and focus groups. The results of these field studies are presented and discussed and the ways in which the data can be incorporated into the model was summarised.

The conceptualisation, design and structure of the agent based models developed are discussed in **Chapter Three**. This chapter outlines the model structure employed for simulations of the dynamics of the water management system in Engaruka. This chapter outlines the issues of scale involved in the development of an ABM of the Engarukan system and the strategy employed to address the issues presented by this. This strategy involved the development of two ABMs to address the specific questions of the research. The summary of this chapter then supports the strategy employed in assessing various scenarios of the functioning of the system which will be discussed in under each of the models.

Chapter Four and Chapter Five present the agent-based models developed in this research. **Chapter Four** presents the Engaruka Sediment Transport and Capture (ESTRaP) agent-based model which addresses the finer scale issues of sediment transport within the North Fields of the field system at Engaruka. **Chapter Five** presents the Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME MACHINE) agent-based model which focuses on the landscape scale dynamics and human decision-making processes that led to the development of the South Fields of the Engarukan system, incorporating the environmental and human factors that would have influenced the development and continued use of the system. The parameters central to the development of these models are explained and data sources for these parameters outlined. The underlying assumptions of the models and the model sensitivity analyses undertaken are also discussed. The scenarios implemented in the models and the results of the analyses conducted are then discussed. The different factors that would impact on the outcomes of the models are discussed based on existing literature and interpretations of the development of the Engarukan water management system.

Chapter Six presents the synthesis of the model results, summaries of the main conclusions, recommendations and future areas of research. The main conclusions from the agent-based models will be summarised and interpretations of the model outcomes and their possible input into the interpretation of the development and management of the Engarukan system will be outlined. Recommendations that can be drawn from this research will be outlined and the avenues for future research will be discussed. In addition, the recommendations will provide additional insights into the ways these outcomes can be applied in contemporary development debates. The ways in which the research can be further developed will also be discussed to address any gaps identified by this research.

1.2 Literature Review

1.2.1 Water-management systems

Water management systems can be defined as the practices that incorporate the control and manipulation of water through landscapes and field systems as well as crop selection based on their water requirements (Adams and Anderson 1988, 522). Scarborough (1991) also defined water management by a society as involving the manipulation of water resources. These systems can also be categorised within the context of agricultural intensification practices that require higher labour input and community investment in human and physical infrastructure (Stump and Tagseth 2009; Scarborough 1991) in order to improve or maintain yields, provide for domestic household needs or support relatively high population densities. Based on these definitions, it is clear that water management systems incorporate a wide variety of activities and can range from simple systems to complex structures. Water management systems can also be incorporated within the use of terraces and irrigation to improve soil and water conservation (Scarborough 1991; Amborn 1989, 71). Water management systems that employ irrigation and terracing practices would incorporate the definitions outlined above in whole or in part, with the irrigation infrastructure such as canals, dams and off-take drainage facilitating the manipulation of water and the establishment and maintenance of these structures requiring significant investment in labour. The establishment of terraces would facilitate soil and water conservation especially in steeply sloped areas by reducing the slope thus decreasing surface runoff and soil erosion and enhancing water infiltration into the soil (Widomski 2011, 317; Ramos *et al.* 2007, 2; Zuazo *et al.* 2005). Crop selection also plays a role in water management systems as the choice of crops grown is not only dependent on the water availability but could also influence the irrigation practices employed.

The rise and decline of water management systems both historically and in contemporary contexts necessitates an exploration into what are the water management systems that existed in precolonial and historical times and what are the main human and environmental factors that influenced their establishment and development. In this work, the focus is particularly on the eastern Africa region where the existing documentation and accounts on these systems are not comprehensive and limited studies had been conducted (Sheridan 2002, 79; Adams *et al.* 1994; Adams and Anderson 1988, 523). This trend is slowly changing with recent studies looking at the historical agronomies and the water management and agricultural intensification practices employed in eastern Africa as well as reviews that consolidate the existing information (Stump 2013; Westerberg *et al.* 2010; Widgren 2010; Stump 2006a; Widgren and Sutton 2004; Sutton 1998); but more research is needed into how the interaction of human-environmental factors influenced their sustainability over time and on a balance of costs and benefits. In particular, this work will look at the historical water management systems of Engaruka and Konso, two systems that are considered analogous to one another but also used as contrasts in debates on the success of the practices they employed.

The response of human societies to environmental changes and stresses such as drought vary greatly from societal collapse to the development of complex water management structures such as irrigation and terracing systems and infrastructure (Costanza *et al.* 2007, 523). Early evidence for the development of water management systems can be drawn from a raft of historical societies (Tarolli *et al.* 2014; Stump and Tagseth 2009; Harrower 2008; Tempelhoff 2008; Stump 2006a; Börjeson 2004; Widgren and Sutton 2004) with some of these systems showing evidence of adapting to harsh climatic conditions. Societies that show evidence of adaptation draw great interest from archaeologists, other disciplines and development organisations with evidence from these societies featuring in debates over the sustainability of the agricultural intensification practices employed (Stump 2010a; Stump 2006a) as well as providing a template for the development of new approaches drawn from these examples.

The historic water management systems in eastern Africa range from simpler systems of opportunistic floodwater cultivation and flood recession farming to complex systems that involve river diversions, water storage and canal and terrace construction (Stump 2010a; Widgren and Sutton 2004; Adams and Anderson 1988). Accounts of flood recession farming can be found for the Pokomo along the Tana River delta and floodplains in Kenya, the Turkana in the floodplains of the

Kerio and Turkwel rivers in Kenya and in the Rufiji valley in Tanzania (Adams and Anderson 1988; Morgan 1974). These practices take advantage of the floodplain environments that tend to get flooded when the rivers overbank during the rainy seasons. The communities would then take advantage of the residual moisture to grow crops in the nutrient-rich sediments that were deposited by the floods (Adams and Anderson 1988). The more complex systems can be grouped based on their geographical location as detailed by Adams and Anderson (1988, 524). The irrigation systems can be found clustered in four main regions of eastern Africa: the northern Tanzania region of the Gregory rift valley between Lake Manyara and Lake Natron; Western Kenya and the Marakwet escarpment in Kenya; the Mt Kilimanjaro area as well as south and east of Mt. Kilimanjaro; and the Konso highlands of southwest Ethiopia (see Figure 1 below). These systems are also considered "islands of intensive agriculture" (Stump 2010a, 1252; Tagseth 2008, 462; Widgren and Sutton 2004).

The east African systems are of importance because we currently do not understand the development of these water management systems in arid and semi-arid regions. Systems that developed in the ASALs (Arid and semi-arid lands) need further understanding as a majority of agriculture in sub Saharan Africa is currently in these regions, where water availability has a great influence on crop production (Rockström and Karlberg 2009; Oweis and Hachum 2006; Agnew and Anderson 1992; Critchley and Siegert 1991). Studies on both extant and abandoned systems, such as on the historical and modern Engaruka system, have pointed to the possibility that the abandoned system may have supported large population numbers, similar to the current population densities; and that the practices employed by the abandoned system might offer solutions to improving crop production to meet population demands. In addition, the sophistication of some of these abandoned systems, such as stream or river diversions using canal systems, as well as the long term maintenance of these structures provide insight into the human and capital resource interventions that were required(Stump 2010a; Adams and Anderson 1988). The information generated from these studies on the historical water management practices can then be employed in development programmes for the design and implementation of contemporary and future interventions. This is an example of the types of comparisons that play out in developmental debates, where extant and abandoned systems are held up as examples of both success and failure of particular interventions as well as acting as the blueprints for the designs of contemporary water management systems. However, as will be explored further in the next section, these debates do not always fully explore or integrate the socio-environmental factors of sustainability in assessing the systems under discussion. This leads to situations in which a single case study can be used as an example both for and against a particular developmental intervention, highlighting the subjectivity of interpretation of existing evidence.

1.2.2 Development debates

The development of water management systems in historical African agronomies are often the focus of academic research and contemporary development agendas, where they are used as examples of water and soil conservation techniques, or in debates on the sustainability of the approaches employed (Stump 2006a, 90-91; Amborn 1989, 79). However, the justification for the belief in the sustainability of these systems is mostly reliant on the longevity of these systems (Stump 2010a, 1252-1253). These claims do not take into consideration the dynamics of the entire agricultural system and the reasons for the establishment of these terracing and irrigation infrastructure. Dynamics such as climate, human decision making, demography, soils and vegetation are rarely integrated or interrelated in these debates when determining how sustainable these systems were over the long term. This is especially needed for eastern Africa where there has only been limited documented research onto these systems, the interactions of human-environment factors and how they influence the longevity and sustainability of the historical agronomies.

In a large number of the early development debates, the support for contemporary development interventions had been based on the idea of a historically “pristine” environment with indigenous African irrigation agriculture practices ignored (Stump 2010a, 1258; Adams 1989, 21). The discussions tended to view historical African landscapes as undisturbed environments where the indigenous people had little influence on the environment and made no major landscape modifications. The concept of a pristine environment was not only supported by proponents of the early development interventions but was also a guiding principle in the early conservation efforts. In the early conservation interventions, existing indigenous agricultural practices were also seen as significantly altering the formerly pristine landscape and as such were considered unsustainable. This raised criticism for the existing indigenous farming practices, which were considered to be poorer performing and unsustainable, in favour of these more modern irrigation interventions as alternatives to increase or improve agricultural productivity. However, the away push from smallholder farming towards 'modern' irrigated agricultural schemes was not only due to the belief that small holder practices were low performing but some other proponents of large scale irrigation held the belief that these practices would offer greater benefits to local people by providing agricultural improvements that would result in higher yields and improve food security. The indigenous smallholder farming practices in sub Saharan Africa were then pushed aside in favour of large scale irrigation systems established in the wave of the successes of the Green revolution in Asia (Adams 1991; Adams 1989, 21; Adams and Anderson 1988, 520).

The potential of irrigation to improve agricultural productivity in sub Saharan Africa has been a dominant theme in both colonial and contemporary development debates (Stump 2010a; Adams 1991, 287). Food insecurity and rainfall variability make irrigation seem to be a viable practice in ensuring water availability for food production in the arid and semi-arid regions. However as in the case of some of the externally imposed irrigations projects based on European and North American farming techniques, they have suffered from poor performance and have been found to be unsustainable over time. However, this cannot be said to be true of all the large scale systems introduced, some of the large scale rice irrigation projects continue to function and provide an example of viable and sustainable systems. In East Africa, the soil and conservation benefits linked to the water management systems have resulted in large investment in irrigation and terracing but the expected outcomes from the large scale irrigation systems have rarely materialised (Adams 1991; Adams and Anderson 1988). This resulted in a change in trajectory with an increased interest in the concept of "development from below" that moved focus to the use of small holder irrigation and the use of indigenous knowledge. Thus, during the 1980s and onwards focus shifted to the previously ignored historical agronomies and their practices, which were then incorporated into some of the government policies across the East African countries for development as models to be built upon, with the belief that their longevity constituted sustainability (Stump 2010a, 1253). The historical systems were then used not only as contrasts with the more modern systems but were also contrasted amongst each other, with aspects from different historical systems (some of the systems are outlined below) used to create arguments for or against the implementation of the practices.

As discussed by Bevan and Conolly (2011), the development of irrigation and terracing systems can require large investments in terms of both capital and societal organisation, thus requiring compelling evidence in order to encourage institutional and government support in contemporary development agendas. However, other systems can develop through cooperative efforts amongst small groups of farmers over time and resulting in large scale systems. This presents a different angle of consideration for the development interventions as this would require more long term planning to allow for smaller stages of development over longer periods of time. The environmental and economic benefits of these systems is also in question; terracing, for example, is considered a good method for improving agricultural productivity in steep and mountainous regions but studies by Ramos *et al.* (2007) and Zuazo (2005) question its viability where they found that large number of terraces can also reduce the available cropping area, are difficult to maintain especially on steep risers, and in some cases the terraces do not reduce erosion due to total vegetation clearing on the terraces and slumping and collapse of terrace walls. Though valid points, their findings only represent one side of the debate: while the terraces might not reduce erosion, this was mainly in cases where the terraces were not being maintained and the same cannot be said for regions where erosion has been greatly reduced by the establishment and maintenance of terraces. And while terraces can reduce the cropping area, this is counterbalanced by their effectiveness in retaining soils on steep slopes and in this sense, retaining the agricultural potential of the land. In addition, the sustainability of these historical systems is in question; for example, the Engaruka field system in Tanzania, along with Konso in Ethiopia, feature prominently in development debates. The complete abandonment of Engaruka in the 18th Century AD is often cited as an example of degradation and ecological collapse while the continued use and occupation of Konso is considered evidence of the sustainability of the practices employed with some of these practices dated at over 500 years old based on oral historical studies (Amborn 1989). However, recent studies conducted on Engaruka have not yielded evidence of ecological collapse of the system such as salinization of soils (Stump 2006a). In addition, the information on these two systems does not detail the intensity and extent of agricultural expansion, the role of human decision making on the expansion of these systems or the influence of the environment on these agricultural practices and in return, how these practices influence the landscape and environment.

It is therefore of great importance to investigate these irrigation and terracing systems to understand the factors that influenced their longevity and sustainability in order to integrate these into contemporary practices. The highly visible archaeological evidence of water management systems globally such as those in the highlands of Peru and the rice paddies of China, feature in a variety of debates on rural development, agricultural technologies and conservation; and while the visible systems from eastern Africa also form part of this debate, the limited supporting evidence from studies conducted in east Africa mean that these arguments can be ambiguous. The structural archaeological evidence left behind by these historical water management systems can provide useful evidence of the existence of intensive agricultural practices particularly of irrigation and terrace farming. However, lack of clear ethnographic and historical information on the establishment and dynamics of these systems places constraints on the ability to use them to develop objective development strategies (Stump 2010a). The water management systems of interest in eastern Africa have been targeted for study in archaeological and ecological studies, and particularly in this research work, because they leave behind highly visible structural archaeological evidence; providing an opportunity to assess long term agricultural practices particularly of irrigation agriculture and terrace farming and therefore assess their viability and sustainability. The human and environmental factors that influence the development of these systems are also not clearly understood. In addition, as has been mentioned above, these historical water management systems provide insight into the human and capital investment required to manage them. In trying to understand the perceptions of the historical societies in relation to their environments we can gain insight into the human decision making that goes into the management of these systems; these insights can then guide development in determining how contemporary communities would integrate these irrigation practices.

1.2.3 Water management in historical agronomies in eastern Africa

A great expanse of literature is available on historical agricultural societies and the water management practices that have been employed, with research ranging from focuses on the hydrology (Harrower 2010; Harrower 2008) to human decision making (Wilkinson *et al.* 2007). Some studies have looked at the significance of these practices on the socio-political dynamics of the society (Widgren 2010; Harrower 2008) while other studies have looked at the environmental impacts of these systems (Stump 2010a; Costanza *et al.* 2007). This background provides a brief overview of some of the literature available in order to answer the questions on what were the different types of water management systems that were employed in eastern Africa and what were the major physical and human factors that influenced their development. The systems of particular interest include those in marginalised environmental conditions such as arid and semi-arid regions as well as societies believed to have developed or survived through a sustained period of environmental stress such as drought. This is because many of the agriculturally productive areas in sub-Saharan Africa are located in the arid and semi-arid regions and savannah ecosystems where water availability is the primary limiting factor and influence on agriculture (Agnew and Anderson 1992) making the soil and water conservation benefits of these systems of great interest (Ramos *et al.* 2007, 2). An example can be drawn from studies on Mesopotamia where settlements in southern Mesopotamia, which relied on irrigation, were larger than those in northern Mesopotamia which employed rain-fed agriculture (Wilkinson *et al.* 2007). Another example would be irrigation in Ancient Egypt that employed the *shaduf* technique, a series of manual water-lifting levers. While these examples fall far outside the regions and time periods of interest in this study, they serve to illustrate how far back water management technologies have been employed by societies.

In sub-Saharan Africa, evidence of the use of irrigation and terracing prior to colonial occupation has been observed in West Africa, Eastern and central Africa, through to Southern Africa (Stump 2013). Observations of these agricultural intensification practices that focused on aspects of irrigation and terracing as noted by Stump (2013), represent a wide variety of approaches to water management and were most probably influenced by different environmental and human factors. The approaches in these societies range from the use of flood recession farming, establishment of contours, terraces and irrigation furrows/canals (Figure 1). These techniques also tend to leave archaeological evidence, unlike other forms of expansive agriculture, allowing for assessment of these historical systems. The structure and complexity of these systems therefore presents a central question to how the agronomies developed and were maintained.

The existence of intensive agricultural systems in eastern Africa has been estimated to date back to approximately the last 600 years (Stump 2010a, 1252). Some of these systems have been abandoned such as Engaruka and Iraqw in Tanzania (it should be made clear that Iraqw is not entirely abandoned but a vast majority of the system is no longer in use) while others continue to serve as important agricultural production areas, such as the communities on Mt. Kilimanjaro in Tanzania and Konso in Ethiopia (Stump and Tagseth 2009; Stump 2006a; Börjeson 2004; Widgren and Sutton 2004).

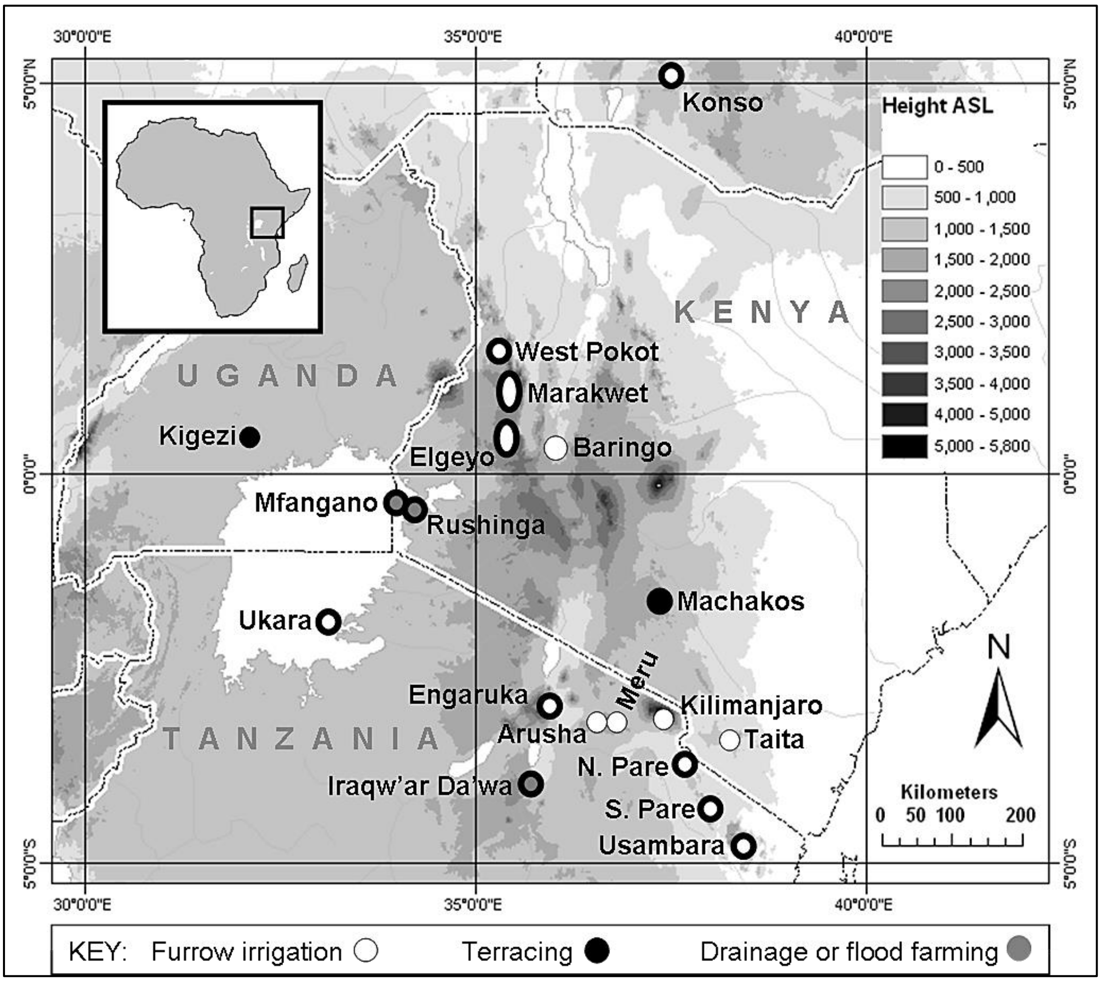

Figure 1: The different types of historical water management systems in eastern Africa detailing the water management practices employed in the different sites (Stump 2010a)

As has been mentioned above, the historic water management systems in eastern Africa ranged from simple to complex systems and as is outlined in Figure 1, the more complex systems employed three main water management practices: furrow/canal irrigation, terracing and flood recession farming with many of the systems employing a combination of these techniques (Stump 2010a). These practices were also supplemented with other soil and water conservation practices such as the use of water storage systems, intercropping, fallowing and the use of animal manure to improve or maintain soil fertility. Based on the three main practices, nine archaeological sites in eastern Africa were identified that employed a combination of terracing and furrow irrigation, with the majority located in Tanzania, five sites employed the use of furrow irrigation while three sites employed a combination of terracing and flood recession farming and two sites employed terracing. The ages of the systems also vary with the Engaruka complex dated to have existed between approximately 1400–1750 AD while the latest being the Baringo system from approximately 1840–1920 AD. However, dating these systems can be particularly difficult and, unlike examples such as Baringo which is well documented in European historical accounts, dates for many others are at best approximations based on limited carbon dating and ethnographic evidence provided by descendants of the societies.

The pre-colonial terraced field systems of Kigezi in Uganda and Machakos in Kenya employed mainly terracing but the dates on their inception are unclear. These terraces could be found on the hill slopes of both these regions with those in Machakos including benched terraces that were levelled while those in Kigezi were not levelled (Carswell 2002; Tiffen *et al.* 1994). The terraces in Kigezi were believed to have been constructed to limit soil erosion and recent studies by Carswell (2002) on the Machakos terraces support these findings.

The systems in Iraqw'ar Da'wa in Tanzania and the islands of Mfangano and Rushinga on the Kenyan side of Lake Victoria employed a combination of terraces and flood farming. While these systems have not been clearly dated, genealogical records for Iraqw and oral evidence for the islands place them at approximately the eighteenth century (Börjeson 2004, 80; Conelly 1994, 182). The terraces on Mfangano and Rusinga Island measured about half a meter tall and were limited to the higher elevations above 1400 where they relied on rainfall; while the cultivation fields on the lower slopes and lakeshores relied on flooding during the rainy seasons (Conelly 1994). In Iraqw, the terraces were also found in the upland regions and measured up to one metre in height; in addition, furrows were employed, but only in the valleys to facilitate drainage (Börjeson 2004)

The combination terracing and furrow irrigation practices comprise the most widespread of the water management systems in eastern Africa with the Ukara system on the Tanzanian side of Lake Victoria, the Kerio valley cluster in Kenya (comprising of the West Pokot, Elgeyo and Marakwet systems), the Pare and Usambara mountain systems, Konso and Engaruka systems. The Ukara system, believed to have been in existence since the 1800 AD, is commonly used as an example of the influence of population pressure on expansion of the irrigation systems. The Ukara systems involved construction of dry stone terrace walls of up to two metres high and furrow irrigation across the island. The irrigation furrow systems in Kilimanjaro date back to at least 1600 AD and tend to be classed with the surrounding systems on the Pare and Usambara mountains. The terracing and furrow irrigation systems in the North and South Pare and Usambara mountains are dated back to the early 18th century and utilised a combination of unlined canals, wooden aqueducts and stone terraces with few stone bound canals (Stump and Tagseth 2009, 113; Tagseth 2008, 464). The terracing and furrow irrigation practiced in the Kerio valley cluster include forty main furrows believed to have irrigated an area of 4000 ha. This cluster is made up of the Pokot and Elgeyo systems which are dated to approximately the early 18th century while the Marakwet system may date from as early as 1600 AD. The furrows were mostly unlined with only a few stone-bound canals in erosion-prone areas and terraces were employed for both agriculture and for habitation (Östberg 2004; Adams and Anderson 1988, 526).

The systems of focus in this study share characteristics in terms of the practices employed and the environmental similarities of the surrounding landscapes. The Engaruka and Konso systems both employed terracing and irrigation canals, and are the oldest identified systems, so far, in eastern Africa. The Engaruka system has been dated to have been in existence from the 15th century while Konso is believed to have been in existence since as early as 1500 AD. The systems can both be found in semi-arid ecosystems and both employed a combination of terracing and furrow irrigation. Engaruka in Tanzania is believed to have developed in the late 15th and function until the late 18th century based on radiocarbon dating prior to its complete abandonment by the 19th century. The site comprises approximately 2000 ha, with stone-bound fields, dry-stone terraces and stone-bound irrigation canals as well as dry-stone habitation terraces on the hill slopes (Westerberg *et al.* 2010; Stump 2006a; Sutton 1998). The field system is made up of three sections (Figure 2), the north, central and south fields with each section having distinct differences from the other (Stump 2006a; Sutton 1998). The north fields, located north of the Engaruka River, and the south fields, located south of the Olemelepo irrigation furrow, were most similar with agricultural terraces measuring from 0.3 metres and up to 3.0 metres high and functioning as sediment traps, as well as the presence of permanent irrigation furrow off-takes. The stone-bound irrigation off-take canals were also present in these fields with further tributary canals distributing water throughout the terraces (Stump 2006a). In contrast, the central fields had no irrigation furrows except on the small hills, and the fields were bound by single layers of stone. The main irrigation off-takes were on the perennial river of Engaruka, and the now ephemeral rivers of Olemelepo and Intermediate gorge; but apart from Engaruka, these other river sources have dried up, which could be a possible reason for the abandonment of the system (see below). The economic activities involved the cultivation of sorghum and various millets, supplemented by livestock husbandry. Konso in Ethiopia is believed by Amborn (1989) to have developed in the early 16th century and continues to be occupied, with oral historical studies placing some of the practices at 500 years old. Different types of terraces and field types were employed in the Konso area due to the differences in topography and the terraces levelled to enhance soil moisture retention. In addition to the terraces, the system also employed the use of drainage gullies to direct excess water. The system is reliant on rain-fed cultivation as there are no perennial rivers in the area (Amborn 1989).

In looking at the overview of available literature on the historical water management systems in eastern Africa it is clear that a wide variety of techniques were employed from flood recession farming to terracing and irrigation farming; and these techniques could be seen as responses to a wide range of environmental and human factors, from the need to intensify agricultural production to meet population demand, to adaptive strategies to deal with soil erosion. This clearly demonstrates that a variety of factors influenced the development of the system and that the influence of different factors can change over time and vary geographically. This is relevant to highlighting the importance of understating not only the primary and the underlying factors but also the interaction of factors in the functioning of these systems.

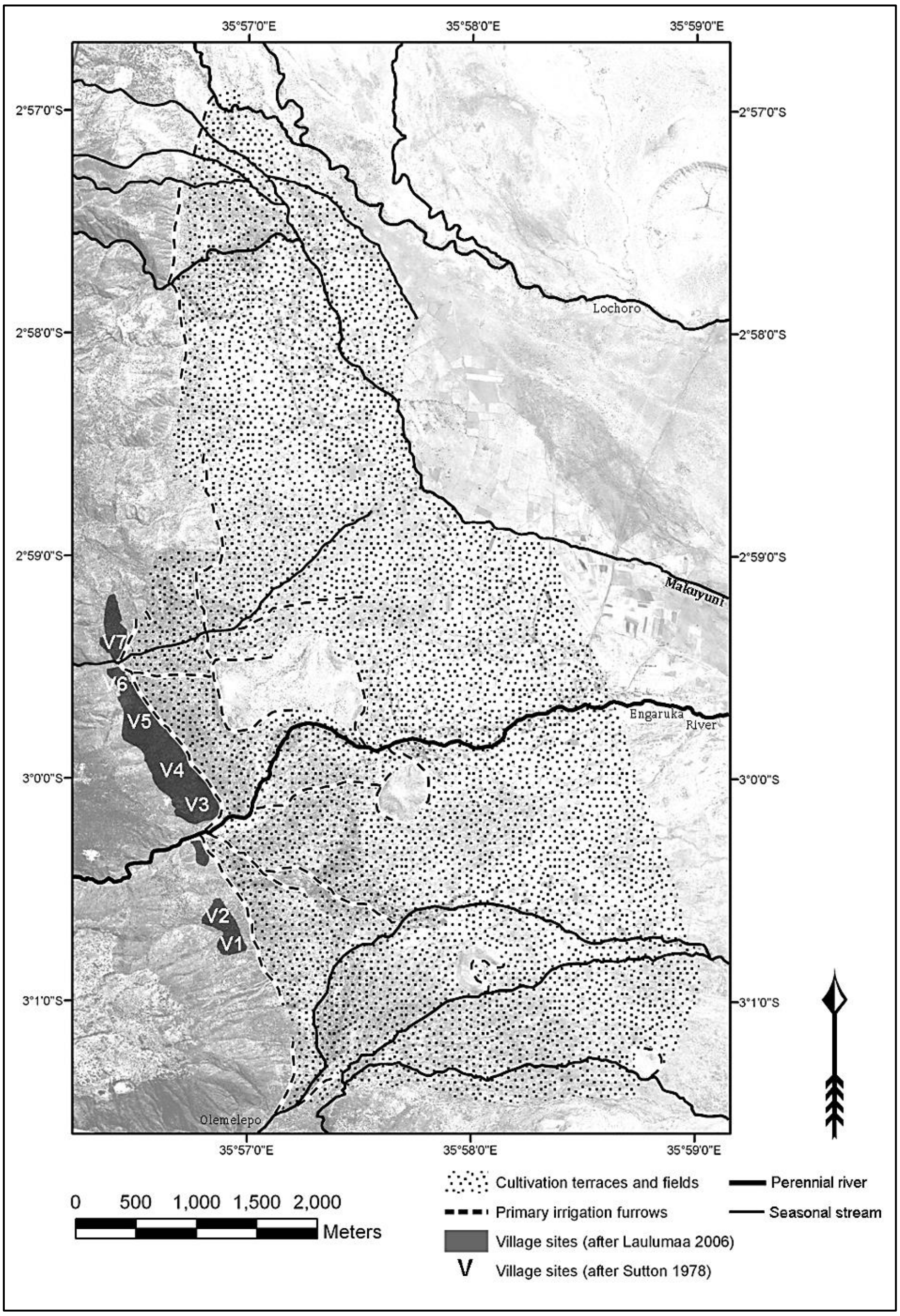

Figure 2: Extent of the Engaruka system with river sources, primary irrigation off-takes and village settlements

The extensive field terracing and irrigation canal system of Engaruka, Tanzania and the hill terracing and floodplain terraces known as *yela* fields in Konso, Ethiopia provide interesting areas of study into the sustainability of historical water management systems. These sites are of interest in understanding historical agronomies that employed irrigation and terrace agriculture due to the preserved archaeological infrastructure that includes dry wall terraces and canals and stone bound fields. In other sites across East Africa for which there is historical ethnographic evidence of agriculture and water management systems, these historical accounts lack physical evidence due to the use of earthworks such as earth bunds and degradable materials such as wood, which are lost over time; as well as destruction of the infrastructure in the course of human resettlement (Stump and Tagseth 2009; Adams and Anderson 1988). Examples of archaeological sites that utilised earthworks and degradable materials include Kerio valley in Kenya and on Mt. Kilimanjaro in Tanzania, where canals were either simple dirt ditches or hollowed out trees and where stone-bounded canals were only used in places of stress. In these sites, the evidence of the historical water management practices include the accounts of the descendants of these communities, archival records from previous archaeological and ethnographic surveys and contemporary evidence of antecedent practices believed to have been passed down through the generations.

Development debates usually cite the Engaruka field system as an example of ecological collapse due to its complete abandonment in the 18th century CE (Koponen 1988, 383), however recent studies have not yielded this evidence of ecological collapse such as salinization of soils (Stump 2006a). Konso on the other hand is considered an example of ecological success (Amborn 1989), but insufficient studies have been conducted on the Konso system to determine if the longevity of the system is due to its sustainability (Stump 2006a). The Engaruka system is of particular interest as it has had limited disturbance from human activity since its complete abandonment, with little of the archaeology being disturbed, which provides an added benefit in trying to map and assess the system.

While both systems employ the use of terraces to reduce slope, improve water retention and act as sediment traps, there are some differences in the systems. The Engaruka system took advantage of the proximity to and availability of, water sources from the rivers that cross the former cultivation area in order to develop a field system using a network of canals that transported the water to fields that were further away from the rivers sources. In contrast, in the Konso system employed rain-fed agriculture and the terraces on hill slopes were designed to trap and retain as much soil moisture on the slopes and reduce runoff. The terraces also had drainage channels incorporated within them to enable runoff of excess rainfall and prevent damage to the terraces. Closer to the river banks, floodplain irrigation is practiced with sediments trapped in what are known locally as *yela* fields to trap both the water and nutrient-rich sediments.

1.3 Environmental and human factors influencing water management

As has been noted in the previous section, the establishment and development of water management systems is influenced by a wide range of factors from environmental - such as climate change, extreme weather events, hydrology, and vegetation change - to human factors such as social structures, trade, war and subsistence and commercial needs. We know that these various factors and the interaction of factors influenced the development of intensive agriculture, and the concomitant water management systems, in historical societies. However, the degree of influence, and the variation in influence, both at the temporal and spatial scale, and the feedback responses of these factors to the systems is still not clearly understood. The east African water management systems discussed above tend to be viewed as full-formed, where the end-product are considered to be the static state of the system throughout its lifetime. This is in many cases not reflective of the reality of these systems where the adaptive behaviour of the societies and the dynamic nature of the systems are not incorporated. This means that more work needs to be done in understanding how systems develop over time, which factors influence the development of these systems; and in the case of Engaruka, and to a lesser degree Konso, what are the primary and underlying factors that influenced its development.

1.3.1 Environmental factors

1.3.1.1 Climate

In semi-arid ecosystems, the amount of rainfall and availability of water resources represent the limiting resource in agricultural production (Oweis and Hachum 2006; Critchley and Siegert). Water availability and the geographic distribution of water resources play an important role in the development of historical societies and in particular agricultural communities. The availability of water can place constraints on agricultural production and the development of human settlements. While it is possible to establish human settlements and the requisite food production in areas with limited water resources, this would require significant investment in the labour and infrastructure necessary for water manipulation (Scarborough 1991, 103).

The east African water management systems outlined above developed within the same time period of the last 1,000 years which was characterised by a historical regional climate fluctuations (Figure 3) that ranged from relatively drier conditions during the 'Medieval Warm Period' (approximately 1000 to 1270 AD) to relatively wetter conditions during the 'Little Ice Age' at approximately 1270 to 1850 AD (Westerberg *et al.* 2010, 305; Ryner *et al.* 2008; Barker and Gasse 2003; Verschuren *et al.* 2000). The wetter conditions that characterised the 'Little Ice Age' seem ideal for the development and expansion of an agricultural system but this was interrupted by three prolonged dry periods that were more severe than any recorded drought of the twentieth century (Ryner *et al.* 2008; Verschuren *et al.* 2000, 412). This begs the question of whether the Engaruka and Konso systems developed to take advantage of the wetter climate or were adaptive responses to the drier conditions faced.

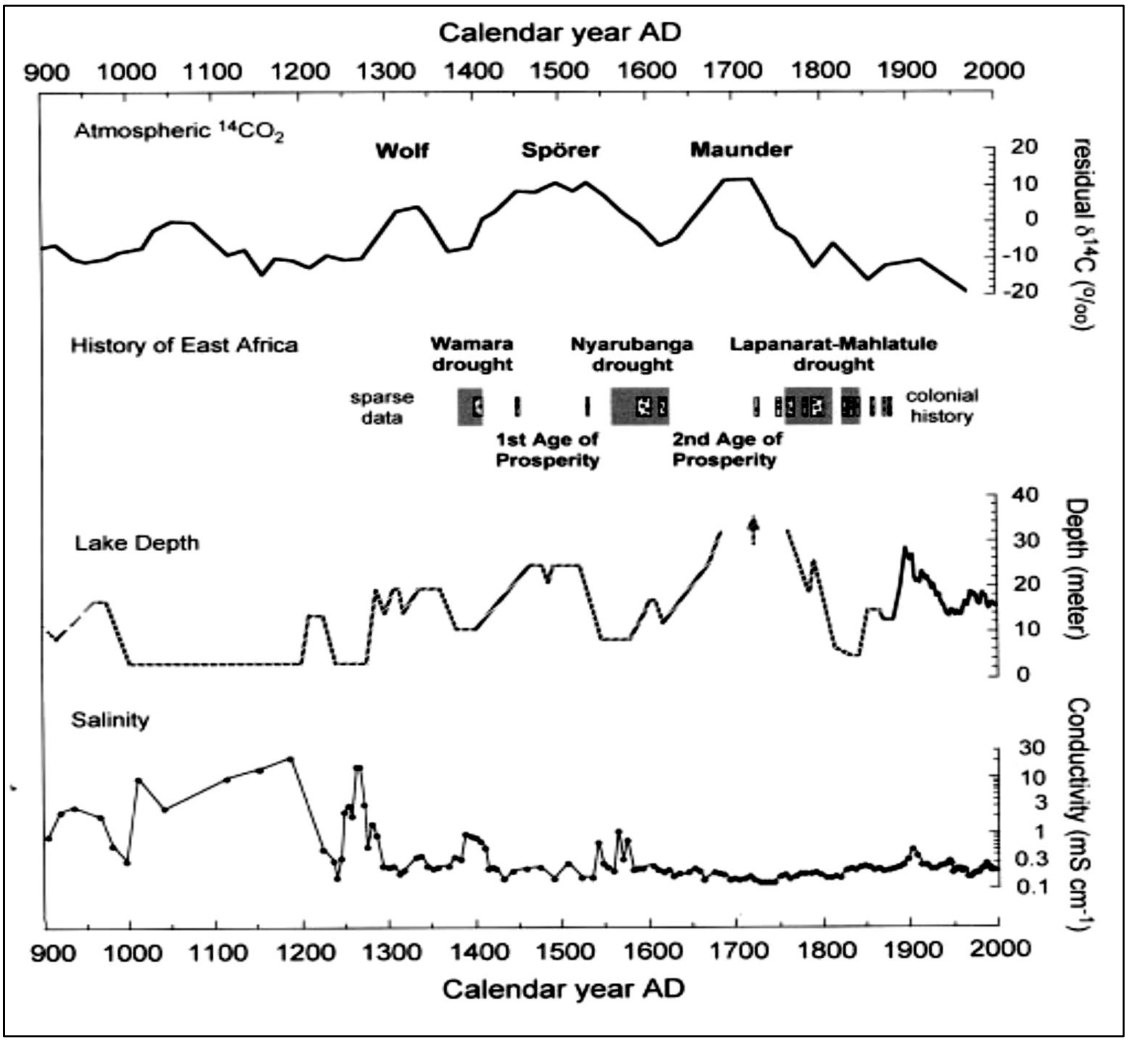

Figure 3: Historical regional climate fluctuations that ranged from relatively drier conditions during the 'Medieval Warm Period' (approximately 1000 to 1270 AD) to relatively wetter conditions during the 'Little Ice Age' at approximately 1270 to 1850 AD, including the 3 periods of prolonged drought during the wetter period (Verschuren *et al.* 2000, 413)

Based on the palaeoclimatic proxy records available for eastern Africa, the water management systems discussed in the sections above developed within the wetter conditions of the 'Little Ice Age' (Figure 3). In studies combining historic environmental conditions with human activity, major societal changes have been found to coincide with certain environmental conditions. For example, periods of drought coinciding with those of civil unrest and large scale migrations, while favourable climates i.e. stabilisation of climatic conditions and extended wet seasons, coinciding with political stability, agricultural development and population growth (Gelorini and Verschuren 2013, 414; Costanza *et al.* 2007;

Verschuren *et al.* 2000, 413). The climatic conditions that governed the eastern Africa region during the period, in which the Engaruka and Konso systems were active, were therefore important in understanding how the communities were able to overcome the limitations of water availability.

Palaeoclimatic records of the Engaruka region (from Empakaai Crater approximately 15km northeast of Engaruka) show that the Engaruka system may have experienced a prolonged dry period around 1420 and 1680 AD (Ryner *et al.* 2008, 598) accompanied by changes in rainfall, infiltration capacity and soil moisture distribution which might have negative effects on vegetation cover and agricultural production (Westerberg *et al.* 2010, 311; Ryner *et al.* 2008). Initially, the wetter conditions of the Little Ice Age might have encouraged settlement and development of agriculture in Engaruka, however the extended dry period might have been the catalyst that led to the development of the extensive irrigation systems in the Engaruka landscape (Westerberg *et al.* 2010, 311; Ryner *et al.* 2008). The wetter conditions and proximity to water sources would have spurred the establishment of the irrigation systems; and as the conditions became drier during the 1550 to 1670 AD, the community would have possibly increased their reliance on the irrigation systems as rainfall became more sporadic. As the dry period continued, the irrigation canal systems could have possibly been extended to take advantage of the proximity of the perennial Engaruka River to maintain soil moisture and crop productivity. The Engaruka system was believed to be at its most expansive approximately 1600-1700 AD, which falls partly within the prolonged dry periods and irrigation furrows would have been extended further away from the river sources to increase the agricultural land (Westerberg *et al.* 2010; Stump 2006a). The wetter period between 1680 and 1800 AD coincided with the continued expansion of the system, however it is not clear how quickly and what were the other possible reasons for the expansion; and this research aims to address some of these questions by modelling scenarios indicating the possible patterns, and highlighting the factors that played a role in the expansion. It was during the 1800s that Engaruka was eventually abandoned despite the fact that this was during the wetter period. It has been hypothesised that the system was abandoned voluntarily due to a shift in economic practices and trade and on a cost-benefit balance between the irrigation and pastoralism, with a possible move towards cattle accumulation and trading (Westerberg *et al.* 2010, 313).

1.3.1.2 Hydrology and Topography

In the east African agronomies outlined above it has been observed that these systems could be found in both high and low rainfall regions such that environmental stresses of low rainfall would not necessarily be the primary reason for the development of the irrigation infrastructure. Local environmental factors of hydrology and topography could possibly have a greater influence on the placement and establishment of these water management structures particularly terraces and irrigation canals/furrows. A defining feature of the water management systems discussed above is the modification of hilly landscapes through the establishment of terraces and in facilitating irrigation by directing water movement through the irrigation canals/furrows.

The proximity of water sources in Engaruka could have been a possible factor in the establishment of the irrigation systems. Studies have shown that the spatial distribution and patterns of water resources and water flow had an influence on the human activity particularly agriculture (Harrower 2010, 1451). Studies in Yemen have found that the placement of the irrigation infrastructure related to the flow water through the landscape because areas of low energy water flows were selected for the placement of diversion channels in order to improve infiltration and sedimentation (Harrower 2008, 502). This is evidenced by the Engaruka system in which the major off-take irrigation canals took advantage of the five rivers within the system, allowing for the irrigation and maintenance of a large area. Canal systems would also be affected by the slope of the land in order to take advantage of gravitational flow thereby minimising labour inputs in transporting water (Scarborough 1991, 102).

In addition to the river system that supported the field system, Engaruka is located within the eastern Rift Valley (Gregory Rift) which consists of a series of small shallow lakes (Marchant *et al.* 2018, 327). The perennial nature of the Engaruka River and the presence of crater lakes such as Lake Empakai on the Rift Valley uplands (Westerberg *et al.* 2010, 306) highlight the influence of watershed resources such as groundwater aquifers that contribute to the river supplies through river springs. While there is little information available on the groundwater aquifers within the Engaruka region they are generally characterised as volcano-plutonic rock formations (Baumann *et al.* 2005, 36). The recharge of groundwater aquifers is reliant on both diffuse recharge from precipitation and localised recharge from surface water bodies such as lakes (Alley 2009). During wetter periods these groundwater aquifers might undergo increased recharge but drier periods or deforestation within watersheds can reduce recharge as well as groundwater levels. In addition, the topography and climate of the region affects residence times of groundwater resources until discharge (Maxwell *et al.* 2016). This means that in steeper landscapes where flows are gained mainly from higher elevations, the residence times are shorter resulting in faster discharge of water. This interplay of hydrogeology and topography would further affect river water supplies and thus influence the supply of irrigation water within the Engaruka field system.

The establishment of terraces also related to the topography and can be viewed as techniques to reduce the slope of the land, improving infiltration as well as reducing soil erosion. The modification of slopes in order to improve agricultural productivity is an important aspect of landscape modification that also influences the hydrology of the system. The terraces of Konso are located on steep hillsides and with no nearby perennial water sources, the system relies on rainfall for agriculture (Amborn 1989). The terraces were developed to help trap soil moisture as well as reduce soil erosion, with drainage canals designed to reduce soil loss from heavy floods. Terraces played a similar role in the Engaruka system and acted as sediment traps for the nutrient-rich sediments from the hill slopes as well as improving soil moisture by reducing runoff thus allowing for better infiltration into the soils. Having seen that there are multiple possible environmental factors, it is necessary to show the many possible human factors that could have influenced the development of these water management systems.

1.3.2 Human factors

The development of irrigation and terracing systems are not usually the result of a single event of large scale expansion but are the outcome of many small-scale responses by individuals and households to environmental and socioeconomic factors. These responses are taken up by multiple agents/individuals within the society and iterated over time, resulting in the development of a complex system (Bevan and Conolly 2011, 1313). The human aspect in the development of irrigation agriculture is reflected in models of population dynamics, political and social organisation, socioeconomic factors and the labour requirements for these systems.

In some of the water management systems discussed above, the expansion of trade and commercialisation of agriculture are cited as some of the reasons for the expansion of the systems. For example, the Baringo community was believed to have established its irrigation systems in order to take advantage of the long distance trade employed along the caravan routes during the late 19th century (Adams and Anderson 1988, 527). In contrast, the Engaruka system thrived during drier periods that coincided with a contraction in the long distance trade within eastern Africa (Westerberg *et al.* 2010, 315). In addition, some of these systems, for example the Ukara system, were believed to have been established in response to population pressure with intensification intended to meet the demands of growing populations but this is countered by arguments that have found that population growth can be as a result of the agricultural intensification rather than the cause, for example in Iraqw (Stump 2013, 6; Börjeson 2007).

Population and labour play a major role in the maintenance and expansion of the water management systems discussed. Looking at Engaruka, the diversion of rivers through off-take furrows required labour investment for building the stone-bound canals as well as in controlling water movement through the system using dams. In other regions such as the North and South Pare mountains the use of unlined canals meant that continuous maintenance was required (Stump and Tagseth 2009, 112). The construction and maintenance of terraces has also been found to be labour intensive with labour required to move the rocks, build and level the terrace soils and maintain the terraces. This is especially necessary as studies have found that the lack of maintenance of agricultural terraces results in soil erosion and landslides (Arnáez *et al.* 2015). An example can be drawn from areas in Konso where the abandonment of some of the terraces has resulted in their collapse, resulting in landslides. The population size ties with labour as with decreasing population, the available labour also reduces, resulting in labour deficits in maintaining the irrigation and terracing systems. In addition, as the benefits of the agricultural production in these water management systems decrease despite the labour inputs, the incentive to continue maintaining the system decrease and the society would possibly move to more economically viable practices. This has been hypothesised as a possible reason for the abandonment of Engaruka with the irrigation system abandoned in favour of pastoralism and the revitalised long distance trade (Westerberg *et al.* 2010, 313).

1.4 Modelling the Engarukan water-management systems

In recent years, there has been growing interest in the use of agent based models in archaeological simulation as they provide an opportunity to integrate human activity with environment response. The use of models and inferential reasoning can help deal with problems of equifinality (convergence of social formations or similar outcomes given different historical processes) and uncertainties (Madella *et al.* 2014, 252). Large-scale agent-based modelling can also be used in archaeology to explore long-lost societies by creating virtual environments to answer questions posed by the archaeological remains such as the growth and decline of Mesopotamian settlements (Wilkinson *et al.* 2007) and the influence of water on population dynamics in an agricultural community (Murphy 2012). However, while agent-based modelling has a strong track record of application in ecological studies, sociological applications have been less successful (Madella *et al.* 2014, 254) due to the complexity involved in modelling human behaviour. In addition, a number of archaeological ABMs developed over the last decade have faced criticism on the approaches employed and their usefulness in portraying human and environmental dynamics. This trend is slowly changing, as noted by Lake (2014), with an increase in simulation models that are applicable to archaeological inquiry. The maturation of the methodological approach, where publications balance description of the simulation methods with comprehensive and applicable results and conclusions, has also helped improve the uptake of simulation (Madella *et al.* 2014, 252).

Some archaeological ABMs developed include on the Anasazi (Axtell *et al.* 2002) aimed to understand land-use and land-cover through settlement and population patterns in relation to maize production with households and populations varying across the landscape and over time. However the model did not find sufficient evidence that climate change was the reason for the eventual abandonment of the system (Lake 2015, 4) and failed to incorporate other factors that could have influenced their abandonment of the system such as labour, cultural pressures or economic incentives. In addition, critiques of the model point out that changes in environmental conditions were imposed rather than being emergent from the model (Wainwright 2008, 661) which makes it difficult to determine if the variability in environment influenced the abandonment. The Village ABM developed by Kohler *et al.* (2012) also models the pre-Hispanic Pueblo societies to understand the factors that influenced their eventual abandonment by incorporating simulations of population size, settlement patterns, resource dynamics and development of social hierarchies. While this model incorporates further human factors, the farmers employ optimisation behavioural strategies for resource production that do not necessarily reflect human behaviour. This is because humans do not necessarily engage in practices that are optimal for productivity but may be guided by other societal norms (see section 5.2 below). The CYBEROSION model (Wainwright 2008) reproduces interactions between the human agents and the environment to understand feedbacks between humans, animals, vegetation and erosion within a landscape. The model shows that the inclusion of human within the landscape would affect vegetation, as would animals and this would in turn have feedbacks to erosion. However while the model represents these interactions across the landscape dynamically, the system is closed and thus external factors of predation or migration into and out of the system, and their effect on the human-environment interactions is not clearly explored. In addition, the human behaviour follows an economically rational strategy which limits responses and human behaviours that would have had further impacts and feedbacks on the landscape. Other models include ABMs coupled with GIS models such as the MedLand project coupled model (Barton *et al.* 2010) that explores the interactions between human settlements and the surrounding landscapes, however, integrating feedbacks between the models can be difficult .

This assessment of some of the ABMs in archaeology shows that there are still gaps in model frameworks which need to incorporate more integrated aspects of human and environment interactions, as well as more nuanced rules of human behaviour that allow for adaptability of agents and emergent behaviour. Further to this, there are difficulties presented when trying to integrate a variety of processes within a geographic setting (Crooks and Heppenstall 2012). The models can be limited not only by the interconnected nature of processes at various temporal and spatial scales, but also by the computational requirements that could hinder incorporation of complex phenomena effectively. In addition, modellers face difficulty in validation and comparing model performance across different settings (Crabtree and Kohler 2012) as the current models developed are specific to the archaeological setting. There is also a need for future ABMs to incorporate different modelling types for more representative simulations of systems (Millington and Wainwright 2016, 4). The challenges in creating integrated or fully-coupled models and modelling human behaviour are discussed further below.

1.4.1 Complexity of Hydrological models

There are a variety of hydrological models available and their use is dependent on the output required from modelling the rainfall-runoff dynamics to simulating hydrodynamics at the catchment and landscape level, and in many cases, these models are necessary as it is simply not possible to measure all the hydrological processes in a watershed (Beven 2001). There are a variety of models that can be used to model the relationship between rainfall, runoff and erosion in a watershed such as SWAT (Arnold *et al.* 1993), TOPMODEL (Beven *et al.* 1995) and KINEROS (Smith *et al.* 1995). The Soil and Water Assessment Tool (SWAT) simulates transport of water in a basin and the contribution of rainfall and surface runoff to stream flow and discharge (Linard *et al.* 2009, 1). SWAT also simulates water management practices such as terracing and application of irrigation water based on specific time steps or on water stress thresholds (Gassman *et al.* 2007, 1213). The Topography-based model (TOPMODEL) is commonly applied to pristine watersheds in humid environments but has been applied to agricultural areas

(Beven 2001). The Kinematic Runoff and Erosion model (KINEROS) is an event-based model that simulates overland flow in arid and semi-arid areas at watershed level, and estimates runoff, erosion, and sediment transport (Goodrich *et al.* 2012, 4; Smith *et al.* 1995). Other hydrological models include the Connectivity Runoff Model (CRUM), that simulates the generation of runoff and overland flow across a landscape during a single storm event for semi-arid environments (Reaney *et al.* 2007). These models represent only one aspect of modelling the hydrological dynamics of a landscape; other models including coupled agent-based and hydrological models as well as agent-based models that look at the human-hydrological interactions, are discussed further below.

The models outlined above represent deterministic or process-based hydrology models, which try to represent real-world physical processes such as rainfall, infiltration, runoff and erosion and could be classed as single events or continuous simulation models (Devia *et al.* 2015). The models such as SWAT and KINEROS are mainly physically-based, requiring physically measurable parameters as inputs, or inputs that are theoretically physically measurable. This would be especially difficult data to obtain when assessing historical systems where data sources might be scarce, or where these inputs would need to be extrapolated from proxy data. These models utilise digital elevation models (DEMs) for the spatial representation of the watersheds and since they are distributed models, they allow for the spatial variation in hydrological processes. The models also range from those that simulate single storm events (i.e. individual rainfall events) to continuous models (i.e. over a long time period that incorporates both wet and dry seasons), and vary in the temporal scales from a daily time step in SWAT to the event scale (i.e. a single storm event) such as in the KINEROS model (Devia *et al.* 2015; Goodrich *et al.* 2012; Moriasi *et al.* 2012, 1243; Chu and Steinman 2009; Linard *et al.* 2009; Gassman *et al.* 2007; Beven 2001; Smith *et al.* 1995). The climatic conditions that the models represent also vary, with TOPMODEL used in simulating humid environments and SWAT for tropical environments, while KINEROS and CRUM are used to represent semi-arid and arid environments.

However, these models have limited human agent interactions factored into them and are limited in scale, either spatially or temporally. While the hydrological models outlined above enable us to assess the dynamics of rainfall, runoff, infiltration, erosion and deposition within a landscape, they have limited inclusion of interactions with human factors, especially when looking at irrigation systems where human decision making plays a vital role. In some cases, coupled models that combine agent-based models with these hydrological models have been designed, and range from models that incorporate agents to understand the runoff and channel flow sources of a basin in semi-arid catchments to more complex coupled systems that look at human decision making and water distribution (Bithell and Brasington 2009; Reaney 2008). Other models that incorporate hydrological dynamics with agency include FlowLogo (Castilla-Rho *et al.* 2015) as well the PANGAEA model, which looked at salinization in irrigation fields in Mesopotamia and decision-making by farmers on the use of fallowing in irrigation management (Altaweel and Watanabe 2012). The FlowLogo model couples an existing groundwater flow models to an ABM that models human decision making in the use of groundwater for irrigation (Castilla-Rho *et al.* 2015). The use of coupled ABM-Hydrology models can present a variety of challenges, with many coupled systems requiring intensive and extensive computational support, both in terms of software used and user technical skills, as well as having limitations in adapting scenarios (Castilla-Rho *et al.* 2015). A particular challenge faced with coupled systems is in their limitations in scenario adaptation, which would require changes to the ABM as well as the hydrological model, in order to synchronise the codes between both simulation systems. This is particularly important when trying to account for different cultural and social behaviour, where there exist a wide range of human responses (as discussed further below). An example can be in the hypothetical case of simulating farmer responses to change in water flows in an irrigation system such as in Engaruka. To explore the responses to other variables or to simulate other social behaviour, such as the cultural differences in decision-making, would require changes to the coding in both models, which can be time and labour intensive. In addition, these models tend to look at the human responses to the hydrological factors, but there is limited incorporation of feedbacks from human behaviour into the hydrology model. This is especially important when looking at irrigation systems where the human responses to environmental factors results in a feedback loop, the consequences of which can be alterations to the environment as part of the human decision-making process. Agent based models that can incorporate the hydrological processes with the human factors and incorporate feedbacks between the environmental and human spheres of the model could potentially fill this gap.

Some agent-based models have also been designed to study historical societies and landscape processes with the aim of understanding how these systems functioned, such as the growth and decline of historical settlements and the influence of water on population dynamics (Murphy 2012; Wilkinson *et al.* 2007). Other models such as those by Isern *et al.* (2012), simulate human decision-making in irrigation scheduling using a virtual irrigation system, in order to determine which are the most viable irrigation strategies. However, these models do not fully incorporate hydrological processes with the human factors represented, which would be of particular interest when looking at the development of the irrigation systems over time. As noted in the start of this section, the choice of hydrological models used is determined by the intended output; however, the outputs from most of the process-based models do not incorporate human factors and interactions, while the coupled models might struggle to incorporate feedbacks from human decision making. In addition, the data input requirements for most of the hydrology models would be restrictive in modelling the Engaruka system given the data scarcity of the archaeological site. In hydrological models that focus on surface water systems, the rainfall-runoff dynamics of a catchment or watershed and simulations of stream or channel flows are the primary functions of these models (Davie 2008; Beven 2001). In studying the Engaruka irrigation system, the dynamics of rainfall, runoff and channel flows are important; however, conventional hydrological models require data inputs that might not be available for this system, given the limited archaeological, physical and ethnographic evidence available for this site. Given the archaeological evidence available at Engaruka, it is postulated that the irrigation system utilised off-take canals from the main waterways, which directed water and possibly sediments into and out of fields via smaller secondary canals; the sediments then accumulated in the fields, which were subdivided into smaller fields of 6m by 6m each, with stone wall boundaries that were intermittently raised as the sediments accumulated (Stump 2006a).

In order to model the possible hydrological processes involved in the Engaruka system, the rainfall-runoff dynamics, erosion and deposition processes and the water flows and sediment transport forces would need to be represented. However, the data inputs to characterise most of these factors would have to come from environmental proxies, given that the system is believed to have been abandoned by the 19th century (Westerberg *et al.* 2010; Stump 2006a; Sutton 1998). Environmental records to assess the climate in Engaruka come from palaeoclimatic proxies such as sediment cores taken from the lakes and swamp within the East African region and analysed to determine the weather conditions and timescales for the given weather events (Westerberg *et al.* 2010; Ryner *et al.* 2008; Barker and Gasse 2003; Verschuren *et al.* 2000). However, while these records can provide an approximation of the weather conditions experienced they cannot provide precise data on the rainfall and runoff generated during these time periods, which would make it difficult to utilise conventional hydrological models. In addition, the archaeological evidence of sediment deposition can be used as a proxy for the water flows generated within the system and can thus determine how much water would have possibly been flowing through the system to deposit the observed sediment volumes. However, this would require more complex understandings of sediment transport and could result in circular arguments where the observed sediment levels would be used to model flow rates and volumes, which are then turned around and used to simulate the rates of sediment deposition. The archaeological site offers alternative evidence in the form of stone lined channels which can be measured, and using the channel sizes and the slope and gradient of the estimated palaeosurface, the water flows in the system can be estimated. This would allow for the representation of different scenarios that incorporate a range of flow rates, which would then allow for the simulation of a wide range of possible sediment deposition rates and patterns. These archaeological proxies present an opportunity to design an ABM that can incorporate simulations of the hydrological processes most pertinent to the development of the Engaruka field system, and utilising the available evidence, to understand the development of the system; and which can be further expanded to incorporate human decision making.

1.4.2 Complexity of modelling human behaviour

The different hydrological models discussed in the section above represent one aspect of the development of an irrigation system, with human decision-making playing a crucial role in the management of water resources. As discussed above, there are a wide range of factors that influence the development of water management systems, from labour to trade to environmental pressures. In addition to these factors, decision-making aspects such as scheduling and division of labour as well as cost-benefit analyses play a role in the management of irrigation systems. However, the wide range of possible human responses, as well as the complexity in understanding human behaviour, makes it difficult to simulate these aspects (Lake 2014; Madella *et al.* 2014, 254). Simulating socioeconomic and cultural factors faces particular difficulty, not only in contemporary societies but also when looking at historical societies, where the hypotheses on the development of these systems are based on subsets of information (Madella *et al.* 2014). One of the challenges in modelling human behaviour has been in the assumption of a rational or optimising individual, which is commonly applied in economic models (Baggio and Janssen 2013, 1742). However, this model does not take into consideration heterogeneity and stochasticity in human decision making from the individual to the institutional or societal level (Castilla-Rho *et al.* 2015; Bonabeau 2002). A wide range of human decision-making models have been developed from empirical models (i.e. from the extrapolation of trends and regression analysis) to process-based models (i.e. that simulate agent triggers and responses), with different aspects emphasised in the different models (An 2012); in addition, human decision making may evolve in response to social and environmental factors resulting in beliefs and preferences changing over time. This presents a challenge in modelling behaviour in historical societies where such dynamics may not leave any tangible evidence (Barton *et al.* 2012, 42). Agent based models of human behaviour present an opportunity to represent actions, interactions, cooperation and the feedbacks from these interactions, utilising simple rules of behaviour (Castilla-Rho *et al.* 2015, 306). The flexibility and ability to represent emergent behaviour, as well as providing real-world representations, makes the use of ABMs to simulate human behaviour a viable enterprise (Bonabeau 2002).

Some models have been developed that incorporate human agents in archaeological studies such as in the growth and decline of Mesopotamian settlements and the influence of water on population dynamics in an agricultural community (Murphy 2012; Wilkinson *et al.* 2007). However, decision-making in these models can be considered simplistic, in part because there is a small range of behaviours relating to water management where agents respond to the environmental conditions, but also in the limited feedbacks that result in landscape alterations or changes in decision making. For example, in Murphy's (2012) model, the agents respond to the availability of water but there does not seem to be any reciprocal feedback of actions to alter unfavourable environmental conditions. In modelling human behaviour in water management systems, a variety of ABMs have been developed such as those outlined above. The FlowLogo model looks at the decisions made by farmers in utilising groundwater for irrigation and how these decisions influenced groundwater recharge, with the aim of assessing the viability of various management strategies (Castilla-Rho *et al.* 2015). The decisions made by the agents on whether to extract water resources as individuals or as a collective, as well as agents' capabilities to perform basic cost-benefit analyses to optimise their profits were modelled. However, the model homogenised farmer use of water resources which would be difficult to extrapolate when looking at the Engaruka where the variations in household decisions would influence how much irrigation water is used, sediments deposited and crop production. Other models look at specific aspects of irrigation management, such as the PANGAEA model where decisions on whether to irrigate and when to leave fields fallow were used to explore the effectiveness of strategies employed to counter salinization in irrigation fields in Mesopotamia (Altaweel and Watanabe 2012). These are a few examples employed in modelling decision-making, particularly when looking at historical societies for which limited information exists on the societal structure, cultural preferences and decision-making processes, which would influence water management.

There exists limited information on the Engaruka irrigation system beyond the archaeological evidence, which presents challenges in modelling human behaviour that tie to how the system developed over time with Barton *et al.* (2012) providing a summary of this issue. Therefore sources of ethnographic data need to be obtained from proxies of analogous societies such as Konso, Ethiopia and systems that are still in use, or for which there is documented evidence. In addition, the agents simulated in the models are guided by rules for decision-making based on behavioural models. There exist a variety of human behaviour models to guide the incorporation of decision-making for the agents in the system. Human behaviour models range from rational models that prioritise maximisation of returns to reinforcement learning models that emphasise learning from experience (Groeneveld *et al.* 2017; Schlüter *et al.* 2017) as well as deliberative, cognitive and neurological-inspired models (Balke and Gilbert 2014).

Rational models tend to assume agents have perfect knowledge of their environment, are goal oriented and prioritise maximisation of utility Monroe (Monroe 2001). However, studies have shown that human behaviour is not always rational and decisions are influenced by other factors such as social norms. Bounded rationality models are a modification of the rational models that incorporate agent self-interest and agents have incomplete knowledge of the environment (Gigerenzer and Selten 2002). These models assume that the agents will assess their choices until they meet their aspirations (Groeneveld *et al.* 2017). Game theory approaches incorporate rational concepts where agents benefit from cooperation with each other, however where there are uneven social dynamics the models do not produce satisfactory outputs of behaviour (Wainwright and Mulligan 2003). Descriptive norm models are based on observed behaviour of agents based on norms that can be injunctive or descriptive (Feola and Binder 2010; Cialdini *et al.* 1991), however these models are limited to the observed behaviour and could miss out on other actions that are not so easily observed. Planned behaviour models incorporate subjective norms of aggregated beliefs that guide uptake of practices and compliance with these behaviours (Ajzen 1991). Prospect theory models incorporate aspects of rational decision-making and agents are weighted on risk aversion or seeking behaviours such that decisions focus on avoiding loss or seeking more risk (Kahneman and Tversky 1979). Habitual or reinforcement learning models make the assumption that behaviour is deliberate and that behaviours become ingrained when there is repeated positive reinforcement and that agents learn from experience (Graybiel 2008; Schlüter and Pahl-Wostl 2007).

Production rule system models are simplified models based on act-react cycles where the agents have a set of actions to employ in response to environmental events or interactions with other agents (Balke and Gilbert 2014, 3). However, the agents are limited in their adaptability and are not capable of effective behaviour in response to conflicting rules. The Belief-Desire-Intention model (BDI) allow for dynamic reasoning by agents as well as heterogeneity in responses. The agents are able to select courses of action based on internalised information on the environment (Belief) that is not necessarily accurate but which the agent believes to be true, their intended goal (Desire) and the plan and resources available to them (Intention) to achieve their goal (Balke and Gilbert 2014). Heterogeneity in responses emerge from these simulations as alignment within the BDI model can vary amongst agents (Özerol and Bressers 2017). However the model is limited in that it assumes bounded rationality in agent response. Cognitive models such as the Physical conditions, Emotional state, Cognitive capabilities and Social status (PECS) models aim to address the limitations of BDI models through condition-state-action rules (Balke and Gilbert 2014). In PECS models simple act-react behaviours of agents' perceptions of the environment, are combined with deliberate behaviour to dynamically model human behaviour. However, little research has been conducted on this system and is currently used as a reference conceptual model.

Modelling decision-making therefore presents a variety of challenges including selection of relevant theories of human behaviour based on available information, gaps in the structure of these theories that result in key behaviours being left out and difficulties in identifying and representing causal relationships (Schlüter *et al.* 2017). Capturing the wide range of behaviours of farmers can be limited when determining the complexity of interactions and heterogeneity in behaviour (Morgan *et al.* 2015, 8) as well as the possibility that even where human behaviour is measured, the behaviour can change over time (Thorngate 2015). In addition, while there are behavioural models such as BDI and PECs that can simulate realistic behaviour, most models still employ abstract concepts (Heppenstall *et al.* 2016, 8). This can make it difficult to adequately represent the key behaviours and drivers of agent decision-making, it is therefore important to incorporate human behaviour modelling concepts to understand human decision-making in the

Engaruka system. In modelling the human responses to water management in Engaruka, there therefore needs to be a balance in representing the most pertinent decision-making processes that are influenced by the socioeconomic and cultural dynamics, with ensuring that the human-environmental interactions are well represented. The actions of the human agents therefore need to be guided by a suitable behavioural model that is supported by ethnographic information on actions undertaken by analogous communities.

1.5 Research Aims and Questions

1.5.1 Aim of Study

The factors that influence the development of these water management systems still remain unclear with different factors exerting varying levels of influence both spatially and over time. The dynamism of these human-environment interactions greatly influences the trajectory of a system. As has been noted, the wetter climate conditions could have encouraged the development of the Engaruka and Konso water management systems. Coupled with proximity to water resources, the climatic conditions have played a role in the expansion and maintenance of the systems. In addition, the role of trade and the cost-benefit of irrigation agriculture versus other economic activities influence the maintenance of these systems. The labour-intensive nature of these systems means that the role of labour is important in their functioning such that as labour costs exceed the benefits, the possibility of abandonment or decline is great.

While some of these systems outlined above show distinct similarities in the practices they employed, the majority of them are not as a result of shared ideas between communities but represent a confluence of ingenuity. The equifinality i.e. convergence of social formations or similar outcomes given different historical processes (Madella *et al.* 2014), in the practices employed makes it even more imperative to understand the human and environmental factors that influenced the development of these two systems i.e. Engaruka and Konso. The aim of the research being undertaken is:

- To model the primary human and environmental factors and their interactions that influence the development of a historical water-management system in eastern Africa, over a temporal and spatial scale.

This is with the intention of understanding how these systems functioned and developed over a spatial and temporal scale. By having a better understanding of the dynamics involved in these agricultural systems, we might therefore be better able to assess the sustainability of the agricultural intensification practices employed. In addition, we might also be better able to assess the perceptions and inputs that affect these water management systems, especially in the face of a variety of environmental stresses, socioeconomic factors and climate change. The modelling research thus forms a critical component of the Archaeology of Agricultural Resilience in East Africa (AAREA) project, the aim of which is to investigate the sustainability and resilience of two historical agricultural landscapes in East Africa (Engaruka, Tanzania and Konso, Ethiopia).

This project is funded by the European Research Council under the European Union's Seventh Framework Programme. The Archaeology of Agricultural Resilience in Eastern Africa (AAREA) project is funded by the European Research Council under the European Union's Seventh Framework Programme Starter Grant Scheme (FP/200702013/ERC); Grant Agreement No. ERC-StG-2012-337128-AAREA was awarded to Stump, D. in February 2014. The project aims to map and model the expansion and resilience of these intensive agriculture systems and explore scenarios to determine if these indigenous agricultural practices can be used as models for economically viable and environmentally sustainable alternatives. In addition, the use of archaeological data in the development of the model will be used to determine the efficacy of such techniques in guiding the development of resource-use strategies at the development planning and policy making levels.

To achieve this, data sets will be recovered and analysed including high precision GPS surveys; data from stratigraphic excavation, geomorphology and dating; archaeobotanical data and vegetation profiles to show vegetation composition and distribution changes across spatial and temporal scales; hydrological data; orthorectified APs, LiDAR and DEM data as well as questionnaires and socioeconomic data. The elements of the system such as the agents and their attributes, agent interactions and the model environment will be developed in order to clearly simulate scenarios; and the reasons for the selection of various agents clearly explained. A Unified Modelling Language (UML) class diagram will be developed to describe the structure of the system i.e. the vegetation, land uses, human decision-making and landscape dynamics and to display interactions. The modelling project will focus on producing accurate reconstructions of the topography and hydrology, as well as estimates of the volume of sediment deposited and the management protocols employed in the two study sites. Combining this survey data with aerial photography, ethnographic data and satellite imagery, along with the creation of a digital elevation model (DEM) that incorporates interpreted archaeological features, an agent based model will be developed to understand the irrigation, terracing, sedimentation and decision-making processes across the landscape.

1.5.2 Research Questions

There have been numerous studies on the historical water management systems specifically those focused on understanding the development of these systems from an archaeological perspective. Many of these studies have looked at the significance of these irrigation and agricultural terracing practices on the sociological dynamics of the society and *vice versa*, such as the political structure, population dynamics and economic factors (Widgren 2010; Harrower 2008). Other studies have looked at the environmental impacts of these systems with the intention of influencing development debates (Stump 2010a; Costanza *et al.* 2007). It has been established that the hydrology of a region has significant influence on the establishment and development of water management systems and that the maintenance of these systems has a feedback to sociological factors. The dynamics of the Engaruka system are also not clearly understood in relation to the wider landscape. It is therefore the aim of this study to develop the research in this area by utilising archaeological evidence, agent-based modelling techniques, analysis of hydrodynamics, DEM data and palaeoclimatic data analysis to answer three questions:

1. To what extent does the incorporation of irrigation canals and sediment trap fields influence the hydrological dynamics and sedimentation processes across the landscape and the irrigation system over time?

Given the large volumes of sediment observed in the terraces, it is important to understand how and when these sediments were deposited. Based on assessments conducted in the field and laboratory analysis distinct layers of sediments were noted (Lang and Stump 2017). The pattern of sediment transportation and deposition therefore needs to be assessed. In addition, combined with analysis of volumetric flow rates, the amount of water needed to transport sediments will also be explored. This is closely tied to environmental factors of hydrology and topography as discussed above where the role of water and the slope of the land could have facilitated the movement of these sediments. By analysing the dimensions of the channels and assessment of volumetric flow rates, the volume of water that can flow through these channels was estimated. Tied to this is how much water is needed to transport sediments and if the channels and terrace walls are capable of containing the volumes of water. This question will also explore how the movement of water occurs, whether in large singular events or in smaller continuous flows that provides the necessary water as well as transporting the sediments.

2. To what extent does the modification of water movement influence crop production and crop yields within the system?

Given the investment into diverting water and trapping sediments, the question becomes whether these actions improve soil fertility and soil-moisture thus enhancing crop productivity. The use of rain-fed agricultural practices versus irrigated agricultural practices will be explored to understand if the additional investment combined with the crop requirements of soil and water result in feasible improvements in yield.

3. To what extent does the interaction of environmental and social factors influence human decisions in the development and continued use of the system?

As has been discussed above, could the wetter climate conditions, proximity to water resources and topography have encouraged the development of the Engaruka system or did the economic benefits of such a labour-intensive system encourage its continued occupation. Combining the information on the soil and water and assessing the crop yield, this question will enable us to understand the effect of the environment and labour needs on the maintenance of the system. Based on ethnographic information and the use of decision-making principles, the human decisions related to agricultural activities will be assessed in order to understand the drivers of the decisions over time. Given the crop needs, water resources available and sediments, would changes in the environment such as droughts or flood events allow for continued use of the system? Or would the labour requirements for maintaining the terraces and irrigation canals accrue a greater cost in comparison to other economic activities? Or would it be a combination of both factors? In combining the above questions we can therefore assess the sustainability of the system over time.

This thesis therefore intends to develop as much as is possible, a comprehensive and replicable technique for the archaeological simulation of dynamics of agricultural systems that will result in comparative results. The modelling strategy, based on the flow diagram and model will provide recommendations for the collection of hydrological, archaeological, ethnographic and other environmental data in order to guide future assessment of other agricultural systems. In looking at the dynamics of past agronomies, ultimately the strategies developed in this thesis will be targeted at contemporary development objectives.

Chapter 2 Methodology and Results

2.1 Overview

This chapter outlines the fieldwork conducted, the methodologies employed in data collection and the results obtained. The areas of study in Engaruka, Tanzania and Konso, Ethiopia are outlined and the rationale for their selection discussed. This chapter focuses on the data and methodology obtained to support development of agent-based models that would represent environmental and social factors that could have influenced the Engaruka system. The methodologies employed include archaeological excavations, topographic surveys, aerial surveys, hydrologic surveys and semi-structured interviews and focus groups. The results of these field studies are presented and discussed and the ways in which the data can be incorporated into the model are summarised.

2.2 Introduction

In the study of historical water management systems and intensive agriculture, the focus has been on the contexts that lead to the development of these systems such as the political organisation, socio-economic factors and environmental conditions. In studies conducted on the development of irrigated agriculture in Eastern Africa, the reasons identified for the development of these systems ranged from population dynamics, political organisation, conflicts and siege situations, cooperative dynamics between communities, trade and economic factors, to drought and water variability and soil and water conservation (Stump 2010b; Westerberg *et al.* 2010; Widgren 2010; Watson 2009; Börjeson 2007; Börjeson 2004; Östberg 2004; Widgren and Sutton 2004). Some of these studies have looked at the environmental impacts of these systems with the intention of influencing development debates (Stump 2010a; Widgren 2010; Harrower 2008; Costanza *et al.* 2007). In some ethnographic studies, the social and political dynamics of the existing irrigation systems have been observed. In studies such as those by Watson (2009) and Hallpike (2008) the social and political dynamics of the communities involved in the management of irrigation systems were studied through ethnographic observations. Other studies such as by Caretta (2015) in Tanzania, look at the gender dynamics in the mobilisation of labour and political structure of irrigation agriculture management.

The majority of these studies focus on single factors that influenced the development of these systems, either on the specific human or the socio-economic or the environmental factors, to try and understand these systems. However, the targeted focus on single factors can often skew our understanding of how these societies and systems develop. In order to understand how the interaction of human and environmental factors influences the development of these systems, we need to look at the longevity, resilience and sustainability of the system, but it is difficult to look at these concepts separately. This is because while these three concepts are interlinked, they represent three different aspects of study for which no one clear method exists. Longevity describes the length of time, but does longevity equate to sustainability or resilience? And if a system is resilient does that necessary mean it is long-lasting or sustainable over time? These and other such arguments have been discussed in a variety of papers, an example of which by Stump (2010a) looks at the interpretations of archaeological and ethnographic evidence to support arguments on sustainability in development debates, and notes that in some cases the same piece of evidence is used to support both sides of the argument. This example shows the nuances that exist in the analysis and interpretations of archaeological and environmental evidence. This is notable in many studies on water-management systems in historical agricultural societies which focus on distinct aspects of the systems and on the consequences of the development of these systems on the human population or the environment (Butzer and Endfield 2012, 3628; Westerberg *et al.* 2010; Harrower 2008; Stump 2006a; Börjeson 2004; Sutton 1998; Amborn 1989). In the end, the impact of the interaction of human and environmental factors is still poorly understood. This research is therefore important in that by incorporating both human and environmental factors we can refine our understanding of the development of the Engaruka system and its influence on both the society and surrounding environment.

As has been detailed in Chapter One and in the paragraphs above, there are multiple possible human and environmental factors that can influence the development of the complex historical agronomies such as those found in Engaruka, Tanzania. These factors interact in various degrees and with varying influence resulting in a variety of scenarios for how and why a system developed.

The use of agent-based models allows a variety of scenarios and factors that could have influenced the rise and continued use of the system to be tested. The models build on the available data to develop a picture of the dynamics of the water-management system and the reasons for the establishment of the terracing and irrigation infrastructure employed in Engaruka. In addition, the models present a cost effective alternative to gathering all the data on the different factors. One of the greatest strengths of the models is the production of answers on the influence of different factors that other forms of data analysis cannot. Agent-based models are applicable across many disciplines from ecology, where they can be used to model population dynamics, to economics, where they are used to analyse current and future market trends and investor behaviour (Crooks and Heppenstall 2012; Macal and North 2010; Macal and North 2009). In this research, agent-based models are used to assess the dynamics of a historical system where the environmental and human factors can be analysed and interrelated over a spatial and temporal scale across multiple scenarios. This involves assessing the dynamics of the historical Engaruka system by utilising archaeological evidence, analysis of hydrodynamics, digital elevation models and topographical data, qualitative data analysis and agent-based modelling, to answer several questions. The three questions to be addressed are:

- To what extent does the incorporation of irrigation canals and sediment trap fields influence the hydrological dynamics and sedimentation processes across the landscape and the irrigation system over time?
- To what extent does the modification of water movement influence crop production and crop yields within the system?
- To what extent does the interaction of environmental and social factors influence human decisions in the development and continued use of the system?

While there are a multitude of factors that can affect the development of water management systems, the model developed by this research focuses on the above specific factors as they are believed to form the backbone of the system in Engaruka. As described in Chapter One and in the sections below, the system was made up of an extensive system of canals. These canals have an important role in the diversion and movement of water across the landscape as well as the sediments that are also transported with the water. In addition, the purpose of irrigation is mainly in order to provide consistent water supplies to crops, therefore the crops grown and their water requirements influence production. The sediments transported also have an influence on soil fertility which influences crop production, and the accumulation of sediments leads to the development of the sediment trap fields. The decisions made by households and collectives of farmers will then have an overall influence on the choice of crops, labour inputs and the management of water.

2.3 Study Area

2.3.1 Engaruka, Tanzania

Engaruka is located north-west of Arusha, Tanzania at 35° 57' 45″ E, 2° 59' 20″ S. The irrigation system is believed to have been in operation during the 15th to the 19th centuries (Westerberg *et al.* 2010; Stump 2006a).The site rests at the base of the Rift Valley escarpment and is characterised by rapid changes in topography from the plains at the Rift Valley floor to the steep slopes of the escarpment foothills (Figure 1). The site covers an area of more than 2000 hectares and has an extensive system of terraces and irrigation canals, which supported several settlements in the area. The region has a bimodal rainfall pattern and currently receives approximately 400 mm of rainfall a year. The topography also influences the climate in the region, with the highland regions receiving much higher rainfall at approximately 1000 mm per annum (Westerberg *et al.* 2010; Stump 2006a; Homewood and Rodgers 1991). The vegetation at the base of the escarpment is characteristic of open grassland savannah ecosystems with low Acacia trees and shrubs, while on the hill slopes it transitions into woodlands and forests. The escarpment is cut into by a series of gorges that contain the major rivers and streams known as Olemelepo, Engaruka, 'Intermediate north gorge', Makuyuni and Lolchoro. The Engaruka River is the only permanent water source with its source high in the Lolmalasin mountains (Sutton 1998, 3). The Engaruka River and the other seasonal rivers drain into the Engaruka basin, containing a shallow seasonal lake (Dawson 2008). The abandoned field system is covered with irrigation furrows set to take advantage of the available river sources(Figure 4), and indeed it is noteworthy that many of these irrigation channels drew water from what are now palaeochannels that rarely contain water (Stump 2006a).

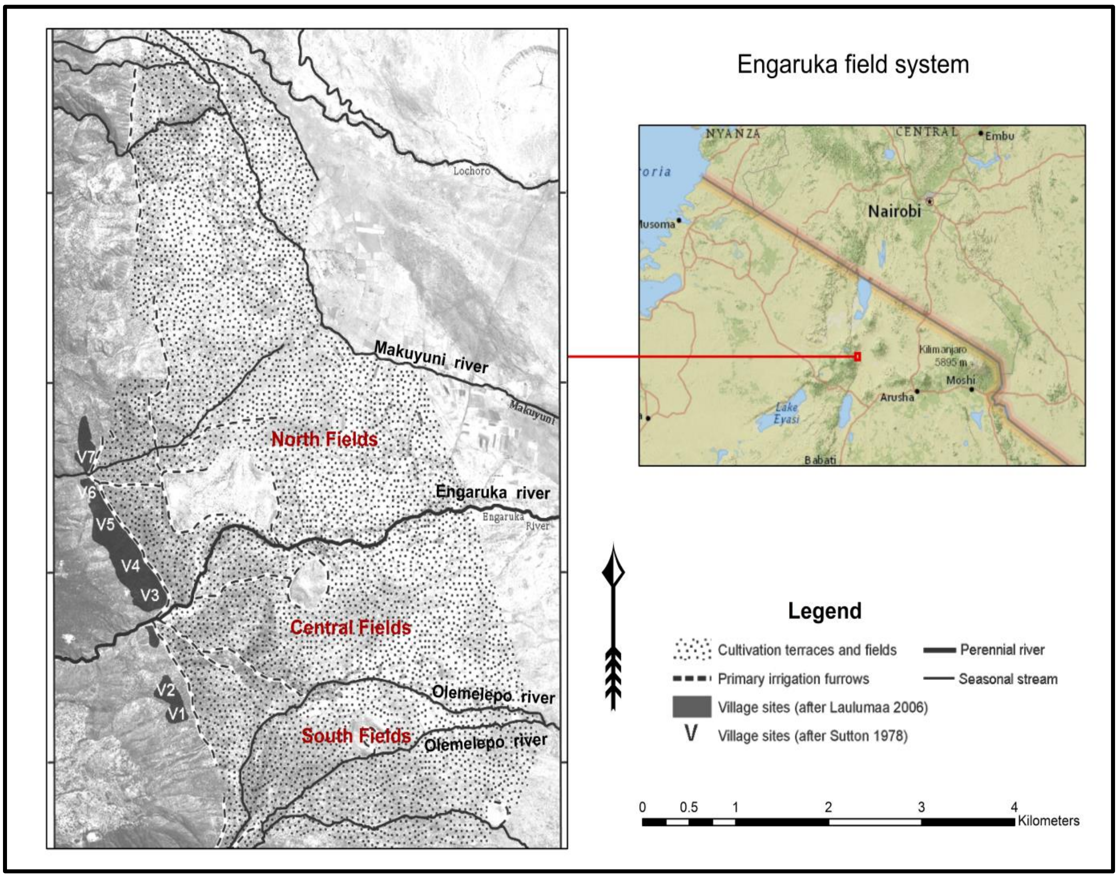

Figure 4: Location of and extent of the historical Engaruka system with river sources and village settlements. Source: National Geographic World Map (Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC)

It is also significant in terms of the hydrological modelling component of the current project (see below and Chapter Four) that there are evident differences in the form and function of field divisions in the lowland area of the site. Sutton (1998) later termed these different field systems as the North, Central and South fields after having carried out extensive archaeological surveys. These excavations demonstrated that these three areas have distinct styles of field divisions while all are comparable in the fact that they are all formerly irrigated arable plots. This is significant to the current study because archaeological excavations within these former cultivation areas conducted in 2002-3 demonstrated that the North Fields - located to the north of the Engaruka River (see Figure 4) – were constructed by periodically capturing sediments that were carried within water channels or canalised streams (Stump 2006a; Sutton 1998).

The differences in the details of field construction in Engaruka were due to the fact that subtly different sequences of field construction could produce the same end result where farmers could accumulate alluvial sediments using low flows over comparatively small areas or instead utilised large flooding events to cover larger areas. The farmers could then have gradually increased the depth of deposits over this wider area over a period of years, decades, or centuries. In order to model this process of sediment capture and the subsequent irrigation of the terraces constructed in this way it is necessary to have detailed topographic data regarding the size and shape of the channels through which these entrained sediments were transported, the slope of the land surface both before and after sediment accumulation, as well as details of the depths of the captured sediments, and to cross reference all of these data sources to the size of the particles transported and deposited, and any changes to particle sizes through time. This was achieved through a combination of topographic surveys in the immediate area of the excavation complemented by aerial surveys over a wider area, and by a hydrological survey of current wet season river flows and of modern irrigation channels that act as analogies for those on the abandoned archaeological site.

2.3.2 Konso, Ethiopia

Konso is located in the southern Ethiopian highlands at 37° 23' 30″ E, 5° 18' 30″ N. The landscape encompasses over 200 km^2 of drystone agricultural terracing, and rests within the Rift Valley and is characterised by a hilly landscape with steeply sloped hills (Figure 5). The area has an extensive system of hillside terraces with the majority of settlements comprising stone-walled villages located at the tops of hills. In surveys conducted by Amborn (1989) in the late 1980s, a complex and extensive terraced field system was documented in southern Ethiopia that formed the Burji-Konso complex. The region is bordered by the Sagan River in the East and South, and the Woito River to the West. The region experiences a dry, afro-montane climate with a bimodal rainfall pattern with rainfall ranging from 300 – 900mm annually (Ferro-Vázquez *et al.*). The soils in the study area are volcanic in origin and the geology of the Konso study area shows that the parent material is primarily basalt rocks. The topography has a significance influence on soil stability, with the soils highly susceptible to erosion due to the steep topography; this has resulted in many hillslopes exhibiting shallow soil depths.

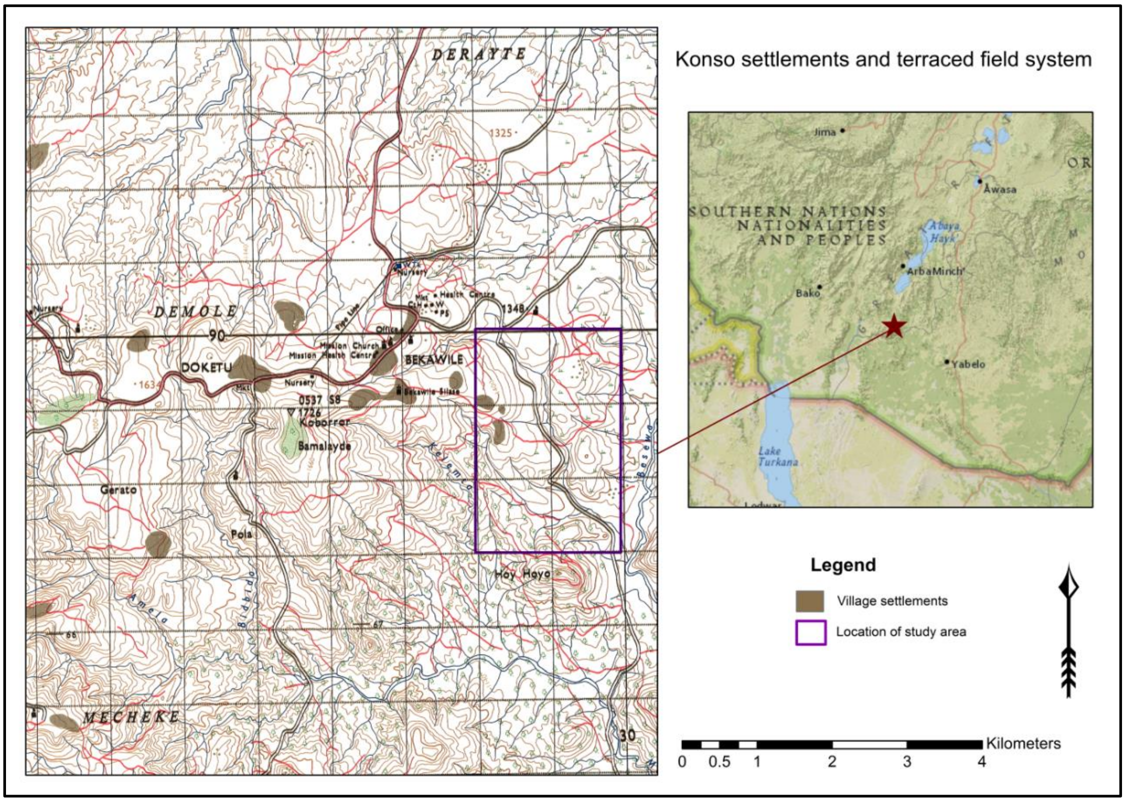

Figure 5: Location of the area of study in Konso, Ethiopia, which borders the UNESCO world heritage site, Konso Cultural Landscape (2011).

The Konso system in Ethiopia is considered to be analogous to the Engaruka system in Tanzania due to the similarities in the complex system of terraces and canals employed in the water management and soil conservation practices of these historical societies. Both systems employ the use of terraces to reduce slope, reduce soil erosion, improve water retention and act as sediment traps. In the Konso system, the society employs rain-fed agriculture and the terraces on hill slopes were designed to trap and retain as much soil moisture on the slopes and reduce runoff and hillside erosion. The terraces also have drainage channels incorporated to enable runoff of excess rainfall and prevent damage to the terraces. Closer to the river banks and in the valley floors, floodplain irrigation is practiced with sediments trapped in *yela* fields to trap both the water and nutrient-rich sediments (Figure 6).

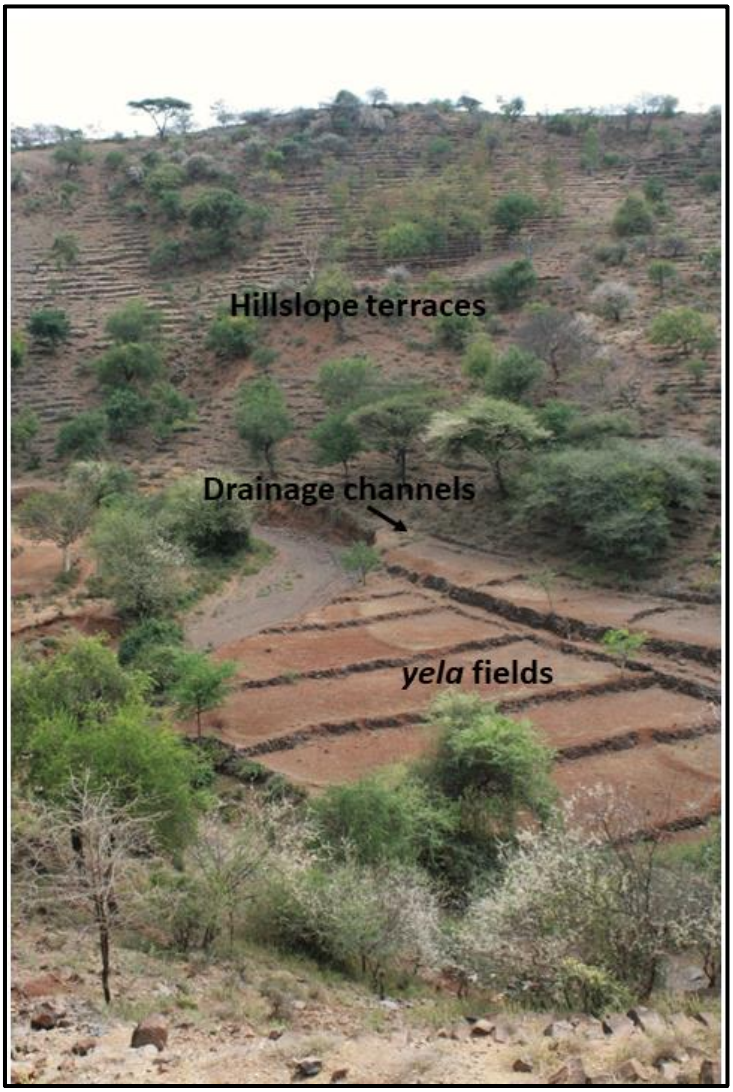

Figure 6: A section of the Konso system of terraces and canals showing hillslope terraces with drainage channels and a valley floor with *yela* fields that trap water and sediments.

The soil and water conservation practices employed by the Konso society are important in understanding the decision-making involved in the management of this and other analogous systems. In order to model the development of the system in Engaruka, it is important to understand the strategies employed by households and communities to maintain these water-management systems. Qualitative methods were employed in order to obtain data on the strategies employed by the Konso society, this data informs the decision-making component of the model as the Konso system is considered analogous to that of Engaruka.

2.4 Archaeological Site mapping

2.4.1 Methodology

2.4.1.1 Archaeological excavations

The excavation site in the South Fields– i.e. the former cultivation area located to the south of the Olemelepo Stream (see Figure 4) was selected as it was highly probable that there were similarities in sediment capture processes in these fields as those carried out in the North fields. Reconnaissance activities found deeply incised gullies that exposed sediment layers and sections of field walls, suggesting deep alluvial deposits similar to those in the North fields. The stratigraphic and geoarchaeological work conducted focused on defining the process of field construction and subsequent cultivation as well as surveying the areas immediately surrounding the excavation locations in order to produce the topographical details necessary to support the modelling of the hydrological and sediment capture processes involved.

The terraces of interest in the Engaruka system were identified and excavated to expose features and understand the processes by which fields were constructed and cultivated. In order to achieve this, the excavation methodology involved the targeted investigation of drystone field walls and stone cairns (in this case rock piles faced with drystone walls) that were either visible on the current ground surface or revealed in the sides of recently incised gullies. Different depositional events or construction events were identified during excavations and each was assigned a unique record number i.e. context number. These unique record numbers were also used identify artefacts or soil samples retrieved from the different layers of depositional events. Removal of deposits such as during construction of irrigation features such as ditches were also assigned unique record numbers. In several locations it was necessary to excavate more than one cross-section through the same man-made construction, for example to demonstrate in which direction water would flow along an irrigation channel, and in such instances the same events revealed in the different cross-sections were assigned different numbers to allow comparisons between the artefacts or geo-chemistry at different locations along the length of the feature. Pre-printed record sheets were used to record observations for each unique event identified. Details included in the record sheets comprised of observations concerning the nature of the event, its relationship to other events, and notes on sediment characteristics and recovered artefacts found. The record sheets also included cross-referenced information on related soil samples, photographs and scaled drawings. Cross-sections (hereafter referred to simple as 'sections') were drawn on waterproof drafting film at a scale of 1:10 cm, and plans (i.e. overhead map views) of individual excavated areas were drawn at a scale 1:20 cm, with the locations of these plans and sections recorded via either a GPS (Global Positioning System)or total station theodolite (TST) as outlined below. Once excavation was complete the reconstructed sequence of all excavated events was compiled into a single stratigraphic matrix in order to try and understand the sequence of events for the recorded stratigraphic data.

2.4.1.2 Topographic Surveys

Archaeological surveys now commonly incorporate the use of Post Processed Kinematic (PPK) GPS, Mapping Grade GPS and a Total Station (Kavanagh and Bird 2000, 257-264), and surveys conducted in Engaruka and Konso employed a combination of these techniques. The topographic surveys employed the use of the Leica SR20 PPK GPS and the Trimble Geo7X differential GPS (dGPS) devices. PPK surveying uses one static antenna that is used to monitor how satellite movement and atmospheric conditions are altering the GPS signal, and a roving antenna that is used to move from one survey measurement to the next. PPK surveying applies post-processed inferential correction rather than correcting in real time, and is used over smaller distances because the conditions further away from the base station will become too different to allow accurate measurement. A total station or TST (total station theodolite) is an electronic/optical instrument used in modern surveying and building construction. The total station is an electronic theodolite (transit) integrated with an electronic distance meter (EDM) to read slope distances from the instrument to a particular point (Kavanagh and Bird 2000, 257-264) as well as recording elevation data.

The survey of each site in Engaruka and Konso was carried out primarily using the Leica and Trimble GPS devices with coordinate data relating to various topographical, archaeological and survey recorded. Topographical maps of the area were used to identify features prior to the start of field work. Identified features within the site were then marked and their GPS coordinates recorded using the two GPS devices and the Leica Total Station. Features identified and recorded included the terrace walls, settlements, irrigation canals, gullies and other features relating to agricultural practices. The Leica GPS, a survey grade GPS, was primarily utilised to record the archaeological details at a high resolution particularly in areas of excavation as well as features smaller than 0.5 metres, while the Trimble GPS, a mapping grade GPS, was used to record details across the landscape and at a slightly coarser resolution of above 0.5 m. At the completion of the season of fieldwork, the coordinate data collected was downloaded and post-processed to improve accuracy (see below).

2.4.1.3 Aerial Surveys

Aerial surveys present a cost-effective survey method allowing users to record archaeological evidence and develop terrain models such as digital elevation models (DEMs) at a high resolution for analysis (Javernick *et al.* 2014). The use of unmanned aerial vehicles (UAVs) to conduct surveys is a relatively new technique that has recently gained importance in environmental and ecological disciplines (Rippin *et al.* 2015; Hugenholtz *et al.* 2013) and offers great potential benefits in the archaeological disciplines. The UAV surveys have a potential benefit over traditional piloted aerial surveys in terms of costs and also resolution of the images generated (Rippin *et al.* 2015; Javernick *et al.* 2014; Snavely *et al.* 2008). The aerial surveys also provide a bridge in the resolution scale between satellite imagery and terrestrial topographic surveys combined with the flexibility in the resolution generated for multi-scale mapping (d'Oleire-Oltmanns *et al.* 2012). The aerial survey conducted in Engaruka, Tanzania involved deploying a DJI Phantom 2 quadcopter mounted with a high definition GoPro Hero3+ Silver Edition camera and the resultant images analysed using Structure-from-Motion software packages to generate point clouds before being input into ArcMap 10.2 to produce DEMs (see below).

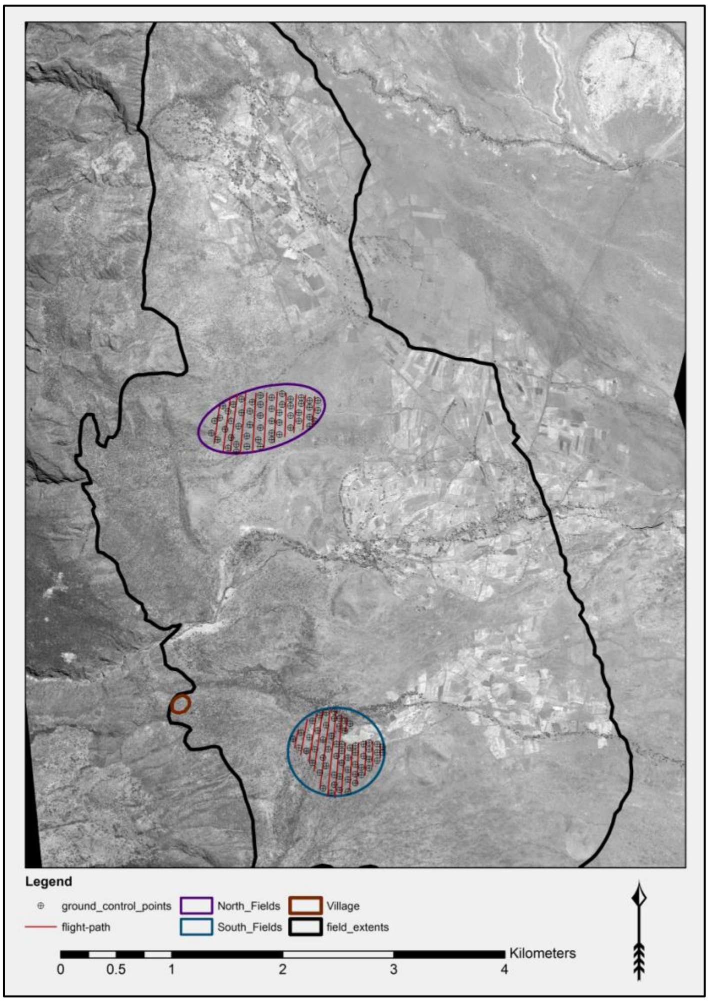

Figure 7: Aerial survey flight pattern over areas of interest in the North and South fields, showing the placement of ground control points

The Engaruka field system covers an extensive area which would have required multi-day data acquisition to ensure the site is fully covered, however time constraints and rough terrain limited the aerial survey to specific areas of interest in the south and north fields (Figure 7). Surveys were conducted in 2016 in the North and South fields, in a North-South flight direction to take into consideration the influence of light on processing of the aerial images. The aerial photographs were taken at a near vertical angle (< 3°) to minimise the possibility of point cloud noise that the vegetation could generate. An overlap of 60% and side-overlap of 30% was the target for the images over a series of survey lines covering the site (Figure 8). This overlap was achieved by limiting the distance between flight paths for each sector within the sites being surveyed, with flight paths approximately 20 metres apart. Each section of the specific sites in the North and South fields was divided into sectors for ease of survey where each sector had approximately 10 ground control points (GCPs) to provide referencing points for the images in post-processing. These GCPs were established using 13cm diameter white plastic plates with crosses of made of bright, contrasting colour overlaid on the plates. Survey height was approximately 25 m to ensure fine resolution of the images produced. Survey height was observed and maintained through the use of a handheld electronic tablet device that communicated with the quadcopter and provided information on the height and speed of the quadcopter as well as allowing the user to view the aerial images as they were being collected.

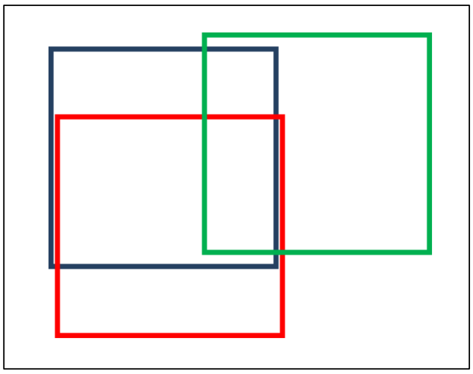

Figure 8: Aerial Survey photograph overlays showing an overlap of 60% (red and blue rectangles) and side-overlap of 30% (blue and green rectangles)

2.4.2 Analysis

After the fieldwork seasons were completed, coordinate data collected during topographical and aerial surveys was downloaded. The results of these surveys were post-processed by georectifying the data for inclusion into multi-scale Geographic Information System (GIS) databases. Post-processing involves the comparison of time-coded signals from the GPS (rover) device, which are used to determine the coordinate positions measured in the field, with those received by a fixed reference (base) station with known coordinates in the same region. Coordinate data are determined using the Global Navigation Satellite System (GNSS) by comparing time-coded signals from a minimum of four networked satellites in the area where data is being collected and triangulating a theoretical position based on the time taken between transmission and reception of the satellite signal. By comparing the coordinate data from the rover GPS devices with those from base stations, the data was georectified to improve the accuracy of the coordinates collected.

Aerial survey image data was also downloaded and processed using the Agisoft Photoscan Pro 0.9.0. The development of high resolution digital elevation models (DEMs) utilising photogrammetry techniques has benefited from recent advances in survey and remote sensing methods. The use of Structure-from–Motion (SfM), a novel digital survey and photogrammetric technique, enables users to generate high resolution DEMs at a lower cost than comparable terrestrial surveys (Javernick *et al.* 2014 180). The term SfM describes a technique that allows for the reconstruction of a three dimensional model using a sequence of two dimensional images taken from multiple camera positions (Rippin *et al.* 2015, 3; Snavely *et al.* 2006, 839). The SfM software packages enable the user to load images and process the data to produce quality DEMs. This research utilises Photoscan (0.9.0) because of its user-friendly interface and the results of studies that have generated high quality data utilising the software (Javernick *et al.* 2014, 167).

The aerial survey images were processed using the established workflows in the Photoscan software (Figure 9). The images were imported into a Photoscan project and poor quality images were removed. The images were aligned utilising the camera angles and time frames before camera alignment was optimised. A dense point cloud was built from the aligned camera positions before building geometry i.e. Mesh of the landscape features. The surface features were then overlaid on the mesh by Building the Texture. In order to effectively georeference the images, after the initial camera alignment and building the dense point cloud, Build Texture was utilised and the GCPs visible within the landscape were georeferenced by assigning their georectified coordinate data, based on the projection system used for the coordinate data. The Build Mesh and Build Texture tools were then used to reanalyse the images at higher resolution to provide a georeferenced orthomosaic of the landscape. The orthomosaic images were then exported for use in ArcGIS 10.2 as tagged image file format (TIFF) and digital elevation model (DEM).

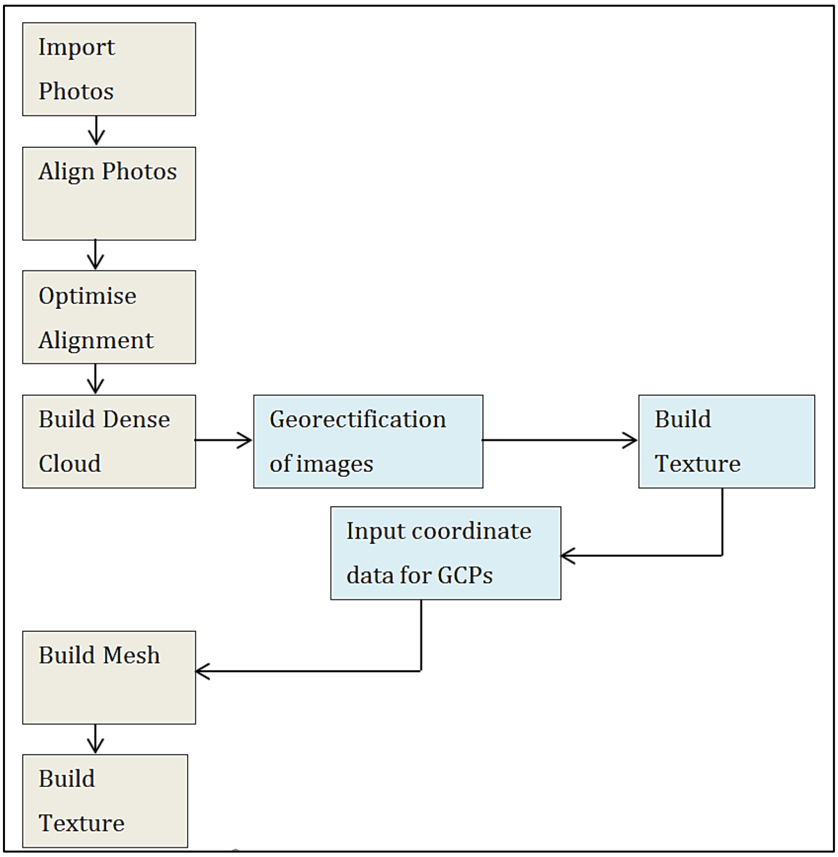

Figure 9: Photoscan workflow for photo-stitching and georectification of aerial survey image data

The data from the archaeological excavations, topographical surveys and aerial surveys were processed using ESRI ArcGIS 10.2 to develop maps of the archaeological features and surrounding landscape. In addition, the DEMs created were analysed using the ArcGIS raster calculator tool to determine the accuracy of the photostitched images. DEMs are single dataset files containing elevation data and are stored in a GIS database as raster or GRID image file or Triangular Irregular Network (TIN) format, which are vector surface models. The DEMs created were analysed using existing DEMs which can be obtained from various institutions such as the United States Geological Survey (USGS). These DEMs are georeferenced to a known geographic or projected coordinate system and pixels in the images are attributed height values. The DEMs primarily used for most of the analysis in this research were obtained from the USGS EarthExplorer the ASTER GDEM V2 released in 2011 with a resolution of 30 metres (1 arc-second) and the SRTM Void Filled released in 2012 with a resolution of 90 metres (3 arc-second). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

Global Digital Elevation Model (GDEM) was developed jointly by the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI). The Shuttle Radar Topography Mission (SRTM) was developed jointly by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA), the Void Filled elevation data was the result of additional processing to improve areas of missing (NASA_JPL 2012; NASA_LP_DAAC 2011).

2.4.3 Results

2.4.3.1 Engaruka

The excavations and topographic surveys conducted in 2014 in Engaruka were primarily focused on the South fields region and the village platforms that overlooked the site. The excavations and surveys conducted in the South fields focused on a field terrace area that had dry-stone walls on three sides and was bisected by a gully which on investigation was considered to be a previously-filled palaeochannel that reopened due to gully erosion (Figure 10). The field terrace studied covered an approximate area of 6,000 m^2 and archaeological excavations revealed the existence of a series of irrigation canals and stone-bound fields in the south fields that were distinctly different from those found in the North fields by Stump (2006a). The three dry-stone walls identified exhibited different characteristics relating to their different roles. The primary terrace wall located on the western side of the field terrace ran approximately 80 metres and separated one set of fields from another. The primary terrace wall functioned as a revetment wall, acting as a barrier to allow for the capture of sediments in the upper field terrace.

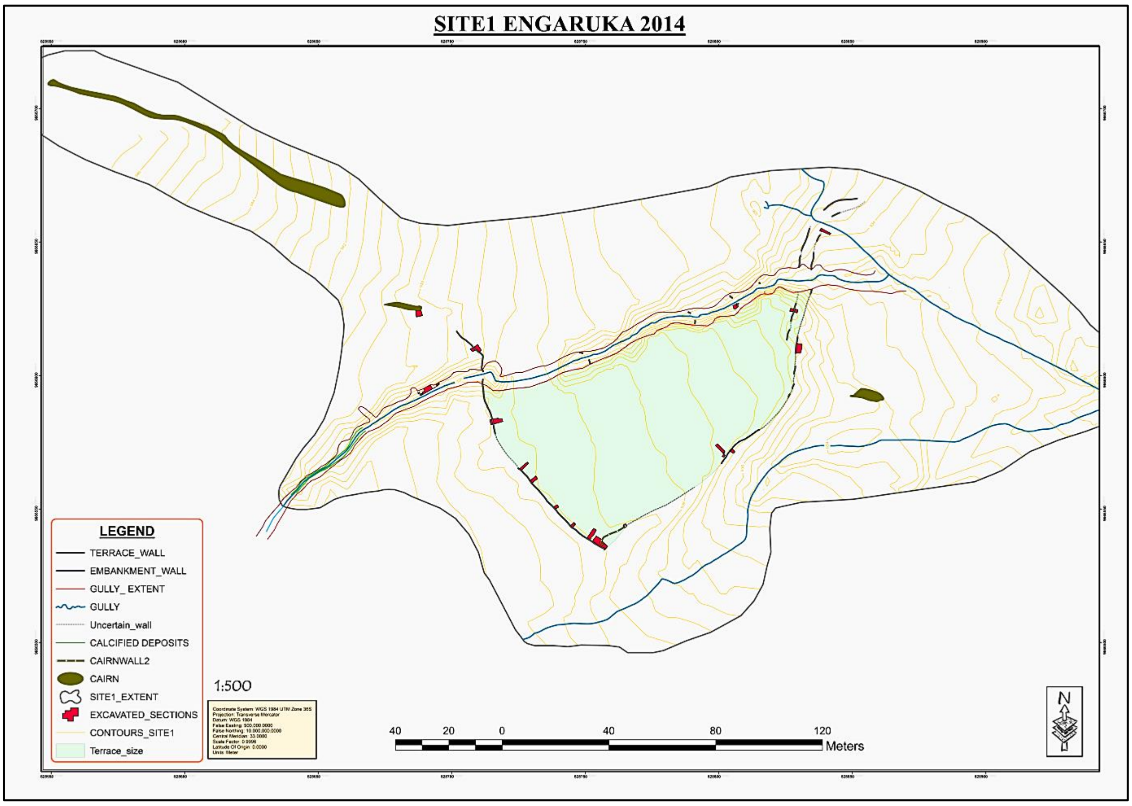

Figure 10: Map of study area (highlighted in blue) in the South fields outlining the field terrace, excavation areas and other archaeological features noted across the landscape

Excavations along this wall, as outlined in Figure 10, found that this wall was not free standing and was not a later addition to the sediments accumulated; instead the walls were inclined such that they rested against the layers of sediments that accumulated behind them and courses were added to the wall as the sediments accumulated. This wall also had the additional function of forming part of the stone-lined irrigation canals used to facilitate the diversion of water from the main water channels into the fields. The irrigation canal utilised this wall to form one side of the canal with the opposite canal wall extended as needed (Figure 11).

The dry-stone wall south of the field terrace and running near-perpendicular to the primary terrace wall in a south easterly direction (Figure 10) was found to function primarily as an embankment wall, with evidence of a water channel found on one side of this wall, running along its course downslope before turning north-eastwards and merging with the eastern embankment wall. The wall could have therefore functioned to prevent the water channel from overbanking onto the field terrace during periods of high water flows while also acting to trap sediments within the field terrace. The dry-stone wall on the eastern side of the field terrace was another embankment wall however this wall differed from the southern wall in that it comprised a set of two walls with the space between the two walls filled with gravel material.

Figure 11: Primary terrace wall (in the background of the image) showing several courses of construction, while in the centre of the image, courses of the irrigation canal wall can be seen. The primary terrace wall functioned both for sediment capture and as one wall of the irrigation canal that ran in front of it.

The aerial surveys conducted in 2016 were used to develop high resolution imagery using SfM techniques. In a comparison with the ASTER GDEM, SRTM Void Filled and Quickbird satellite imagery, the photo-stitched aerial survey imagery had the highest resolution at 0.25m this is in comparison to the satellite imagery that had a resolution of 0.7m and the GDEM and SRTM at 30 m and 90 m respectively (Table 1). The higher resolution allows for smaller archaeological features to be assessed within the context of the wider landscape.

Table 1: Comparison of resolution of image datasets for analysis of topography and archaeological features

Dataset	**Resolution (metres)**
SRTM Void Filled	90
ASTER GDEM	30
Quickbird Satellite image	0.7
Aerial Survey image	0.25

Analysis of the aerial survey images reveals additional details on the pattern of placement of irrigation canals and sediment trap fields within the landscape. Adjusting the colour spectrum on the images also allows for more features to be observed (Figure 12) showing sequences of fields that were otherwise unclear. The irrigation canals were angled to take advantage of gravity to support the movement of water, with canals built heading downslope and the angle of the off-take for the irrigation canal improves discharge while minimising possible damage to the channel walls.

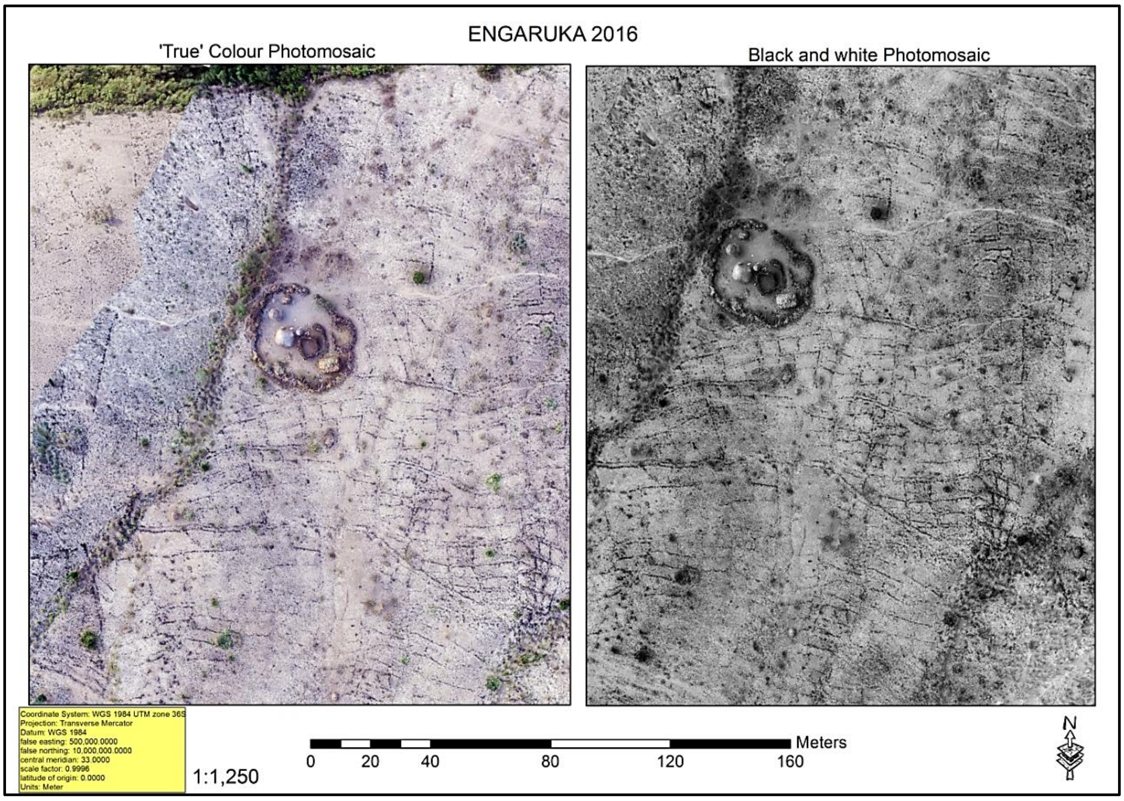

Figure 12: Orthomosaic photo of aerial survey imagery from Engaruka, in the South fields at scale of 1:1,250. The high resolution imagery reveals a series of stone-bound fields and irrigation canals with little degradation of the image as compared to satellite imagery at the same resolution

The irrigation canals were set at oblique angles to the natural water channels, with the approximate angle for the off-takes at 120˚. The stone-bound fields were also angled away from the irrigation canals this allows water to be diverted into the stone-bound sediment trap fields at a fast enough rate to cover the field without causing damage to the field walls. The irrigation canals were also spaced out along the water channels to ensure adequate coverage of the fields before any additional water was carried out of the system downstream.

2.5 Hydrology

2.5.1 Methodology

The hydrological and sediment sampling was conducted in May 2015, after the long rains that usually occur between March – May, conditions during this period were dry with no storms or rainfall incidences during the sampling period. Sampling encompassed sections of the Engaruka and Olemelepo Rivers as well as irrigation canals that fed into the modern section of the Engaruka farming area. The samples were collected after the rainy period had ended, during moderately warm weather during which there were no storms within the Engaruka area. The Grab method was used to calculate the amount of suspended material. This involved taking water samples of known volume, and pumping the samples through a pre-weighed filter. Weighing the dried filter afterwards gave the sediment content in weight per volume (Davie 2008; Hudson 1993, 79). Measurements were conducted at several points along the Engaruka River as well as at points along the off-take channels and focused on the water body with bed-load (i.e. particles transported along the river bed through rolling, gliding or saltation) considered to have negligible effects (Figure 13). Five replicates were collected at each sampling point and the dimensions of the Water channels, water depth and pH of the water was also measured at these points. After fieldwork, the samples were air dried in a fume hood to prevent contamination for a week. The dry weight of the samples was then recorded using an analytic balance accurate to 0.01 grams.

Figure 13: Hydrological and sampling practice showing a) the collection of sediment samples using the Grab method, b) one of the irrigation canals leading into the modern fields sampled for sediments and to determine water channel dimensions, and c) water depth and river channel width measurements using a tape measure and ranging pole across the river channel.

2.5.2 Analysis

The dimensions of the gullies and canals, obtained from the topographic surveys, were used to calculate water flow rates within these channels. The gully, which is believed to be a former palaeochannel, was surveyed at eight points along its course which was adjacent to the field terrace studied during the 2014 field study (Figure 10). The adjacent canal was also surveyed. This was in order to assess how much water could effectively be transported through the channels as well as the influence of flow rates on sediment transportation and deposition. Flow rate in the channels was estimated using Manning's equation (Eq. 1) (Robert 2014, 31):

$$Q = \frac{k}{n} * (R)^{\frac{2}{3}} * \sqrt{S} * A$$

Equation 1

Q represents the water discharge ($m^3\ s^{-1}$), A is the cross-sectional area (m^2), R is the hydraulic radius (m) and is equal to A/P. P is the wetted perimeter (m), S is the slope of gradient of the stream bed ($m\ m^{-1}$) and n is the Manning's roughness coefficient (dimensionless).

$$V = \frac{Q}{A}$$

Equation 2

V represents the velocity ($m\ s^{-1}$) of the water flows through the channels is a function of the water discharge Q and the cross sectional area (A).

Total suspended solids (TSS, $mg\ L^{-1}$) were determined as the difference between the dry weight of the filtered sediments and the filter as a ratio of the water volume:

$$TSS = \frac{R_w - F_w}{W_s}$$

Equation 3

R_w is the dry weight of the residue of the filter (mg), F_w is the dry weight of the filter alone (mg) and W_s is the volume of the water sample in litres (L).

The results of the analysis of total suspended solids were statistically analysed for variances in the volumes of suspended sediments along the channels using ANOVA testing.

2.5.3 Results

Based on the channel dimensions and a probable maximal water depth corresponding to the tops of the channels, the water flows within the gully were found to be higher than those from the neighbouring canal (Figure 14).

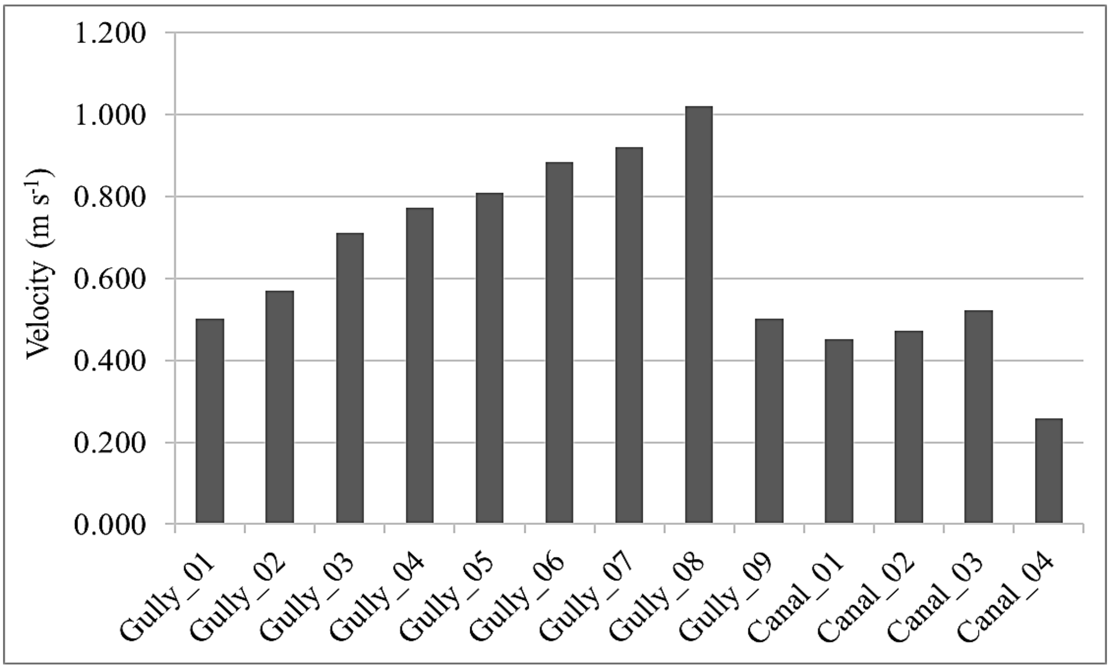

Figure 14: Velocity of flows within the channels approximated using channel dimensions obtained from topographic surveys

The water flows increased incrementally from the upper reaches of the gully to the downstream before decreasing as the channel narrowed and became shallower. The water flow rates within these channels fall within Hjulstrom diagram values of 0.2 – 5.0 m/s for the transportation of sediments, particularly clays and silts and fine sands. The flow velocity within the channels was also low enough to prevent erosion of the channel surface.

Table 2: Dimensions of the channels surveyed, cross-sectional area and slope

Channel type	**Cross-sectional Area (m^2)**	**Channel slope (m/m)**

Gully / Palaeochannel	0.91	0.028
Canal	0.78	0.016

The differences between the flow velocities in the gully and canal can be related to the differences in channel dimensions with the gully having a wider and deeper channel as compared to the canal. In addition, the gully had a slightly steeper slope as compared to the canal which would have resulted in higher flow velocities (Table 2).

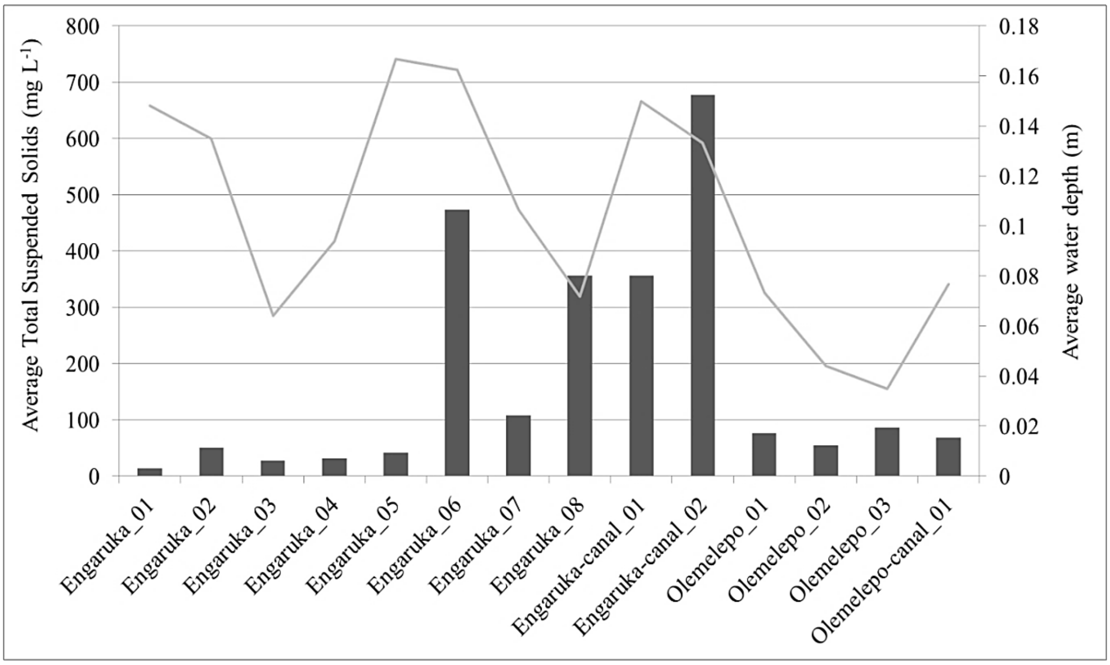

Figure 15: Total suspended sediments determined along the contemporary Engaruka and Olemelepo rivers and neighbouring irrigation canals

The Total Suspended Sediments within the river channels differed significantly along between the river channels and the neighbouring canals [F (13, 56) = 2.57, p = 0.007] (Figure 15). The Engaruka river also had significantly higher TSS values as compared to the Olemelepo river. This could have been due to the nature of the channels particularly in relation to channel surface roughness. The river channels were noted to have gravel bottoms and vegetation along the banks which would act to prevent the erosion of material into the water channel. The irrigation channels on the other hand, were earthen channels and the channel banks tended to be bare allowing for the erosion of sediments into the water column. The water depth fluctuated along the course of the different channels, however, there was no significant correlation between the water depth within the channels with the volume of sediments transported.

Based on studies conducted by Stump (2006a), the soils in the Engaruka field system are believed to have accumulated through sediment accumulation in the fields from suspended material that was transported in the rivers and irrigation canals before being discharged onto the fields. The transport and capture of sediments across the Engaruka landscape are closely related to the hydrological dynamics of the river channels and irrigation canals utilised by the farming society. This ties closely with the flow rate of water within the channels as the fast moving water will transport larger pebbles while slower flow rates would be transport silt, sand and clay (based on interpretation of the Hjulström-Sundborg diagram) (Miedema 2010; Sundborg 1956). This means that it is likely that the sediments were transported in proper suspension, i.e. not through rolling, gliding or saltation. In this way, the desired sediments would be carried in the channels and deposited in the fields.

2.6 Farmer decision-making

As discussed in Chapter One and the sections above, the socioeconomic factors and decisions made by households and the overall social structure involved in the management and development of an irrigation system play an important role. In order to understand the choices involved in water and labour allocation, choice of crops and response to shocks or uncertainty within an irrigation system, the society involved in the development and management of the system, needs to be understood. However, the decision–making processes that influenced the development and expansion of the Engaruka society would be difficult to assess as the system has been abandoned and the current occupants in the surrounding region bear no common ancestry with the previous occupiers of the irrigation system. In order to try and assess this historical society, qualitative research on communities and societies that employ water- management practices similar to the historical Engaruka irrigation society can provide insights on the decisions involved in the management and development of the system, for example, the Konso of Ethiopia. In addition, local perceptions within the contemporary

Engaruka communities and their responses to existing environment conditions were also assessed to take into consideration local contemporary decision-making in water management. The findings of these studies can then be collated with data from other research as outlined above to develop an agent-based model of the possible decision-making scenarios employed by the historical Engaruka society that influenced the development of this system, as discussed in the sections below.

However, there are some issues in the use of modern rules of a community's behaviour to infer past behaviour of other similar communities from them. While analogous communities both in terms of geographical or cultural contexts present an important resource in highlighting practices of past societies, there is the assumption of continuity in cultural knowledge and motivations of these communities (Sillar and Joffré 2016, 657; Lane 1994, 57). There is thus the possibility of assuming that the practices employed have not changed over time and are static in the face of environmental and social factors. In addition, these interpretations can fail to identify unique practices that were employed by the past communities that may have been lost to the modern ones (Minnis 2004, 254). One of the positives of the use of modern ethnographic studies is that it can also capture variations in practices that would otherwise not be notable through reliance on the archaeological evidence alone lane (Lane 1994, 59). In this way the research can expand interpretations on the practices employed by past societies. Thus, in order to try and avoid some of the pitfalls discussed above, the research conducted focused on the variety of actions and activities that the farmers in these modern communities would engage in and their responses to environmental factors for irrigation management. In this way the research does not try to infer cultural motivations that might not necessarily be true of the historical community and allows for variations in practices.

Within the context of the main research aim, the qualitative surveys intend to address the question: *What were the preferred strategies and practices for the management of water and labour and in response to uncertainty in the terraced and irrigated landscapes of Engaruka, Tanzania and Konso, Ethiopia*.

The community in Konso has been the subject of previous studies by Hallpike (2008) and Watson (2009) as they are considered an example of long term sustainable intensive agriculture with the community believed to have been in existence for over 500 years. The contemporary community in Engaruka is an example of intensive agriculture, particularly in water management and scheduling practices where water allocation and scheduling play an important role.

2.6.1 Methodology: Interviews and Focus Groups

Data was gathered in two communities, Engaruka, Tanzania and Konso, Ethiopia between 2014 and 2015. The respondents for this research were selected based on a combination of discussions with local community representatives and research into the communities in the study areas. In the study conducted in Engaruka, a sample of ten farmers was interviewed, with the respondents selected after initial discussions with identified community leaders and on the advice of local assistants who have worked on previous ethnographic studies conducted in the area. In the Konso study, a total of 27 farmers were selected based on discussions with local community leaders and community selection of representatives. The qualitative methods employed included ten interviews in Engaruka and in Konso, six interviews and two focus groups made up of ten people in each focus group were conducted. The difference in the number of respondents in the two study area was because in the Engaruka study, only interviews were conducted while in Konso a combination of interviews and focus groups were conducted. Respondents in the focus groups and interviews did not overlap, such that no respondent participated in more than one interview or focus group. The criteria for the selection of respondents included was primarily focused on those actively farming, residing within the study area, and engaging in intensive agricultural practices of irrigation and terracing. This resulted in a respondent pool of mixed genders and different age groups. In order to provide focus during interviews a series of set interview guide questions were prepared to ensure the topics of interest were sufficiently explored. In Engaruka, the interviews focused on irrigation water scheduling and maintenance of fields and canals. In Konso, interviews and focus groups focused on the theme of energetics i.e. the amount of time and energy invested in farming and maintaining the hill slope terraces and the *yelas*. The concept of energetics encompasses issues of energy and time and their influence on resource utilisation (Worthman 2003, 294). Information to guide questions on soils was obtained from literature from previous studies conducted in Engaruka and Konso that described general characteristics of the soils in the regions (Westerberg *et al.* 2010, 311; Amborn 1989). In addition, representative soil samples of the different soil types were collected and used to support the respondents' descriptions and ensure consistency in reporting, particularly in cases where a soil type was known by different local names.

Respondents were only interviewed once and there must be noted the possibility that responses might be distorted due to personal biases as well as the possible personal dynamics that could have arisen within the mixed-gender focus groups. In order to counter this possible distortion, triangulation, i.e. using more than one method to collect data, was utilised to improve the assessment of the findings and to capture different dimensions of the findings (Barbour 2001). This included the use of a combination of interviews and focus groups with quantitative data and field observations. As outlined below, the interviews and focus groups covered a variety of themes to build an overall understanding and gain insight into respondents' practices. In addition within the focus groups, to reduce the risk of individuals within the group being excluded, respondents were usually asked to give their opinion on an issue individually and then allowed to discuss as a group to allow for consensus or contradicting opinions to emerge. However, as outlined above, the main focus of this study was on identifying the preferred practices and responses employed by the respondents in managing water allocation, labour and energy requirements in their farming.

Research activities

Interviews in Engaruka were conducted in Kiswahili and in the Maasai language with the aid of a translator, recorded and transcribed with the help of assistants. The discussions conducted covered three main themes: Irrigation practices, soil characterisation and farming practices, and responses to extreme events (Table 3). In order to streamline soil characterisation, samples of the different soils identified were collected and used for the purpose of soil type identification by respondents. The age, gender, primary occupation and ethnic identity of the participants were also recorded.

Table 3: Summary of Interview guiding questions for the interviews conducted in Engaruka, Tanzania

Farming and Irrigation Practices
1. Please explain the process you follow in preparing your fields/ farm for irrigation? a. Do you remove stones? b. Do you add manure? 2. Do you have smaller furrows in the farms to direct water to the crops? a. If not, please explain why? b. If yes, please explain how you arrange the small furrows in your farm? 3. Do they allow for fallowing between planting seasons? 4. Do they practice crop rotation? 5. Do they incorporate additional inputs such as manure or fertilisers in the soil? 6. What do they do with the manure in the animal pens? 7. After harvesting, do they allow livestock to go through the farms and eat the crop remnants? 8. Was the water management practice of irrigation scheduling developed by the community?
Soil Characterisation
1. Please explain the different types of soils that you are aware of in the Engaruka farms? 2. Can you describe the different soils? Texture? Colour? Quality? 3. What crops that you can grow on the different types of soils? 4. Do you add manure to the soils? 5. Are there any practices you employ to ensure the soils remain fallow?

Extreme Weather Events
1. Please explain any floods and droughts that have occurred? The time period? 2. What do you do if your farm does not receive any water from the irrigation system? 3. What do you do if there is a drought or there is extreme rainfall or flooding?

Interviews and focus groups in Konso were conducted in the local Konso dialect (Konsinya) with the aid of a translator, recorded and transcribed with the help of assistants. The discussions conducted covered three main themes: energetics, terrace history, construction and maintenance, and landscape and climate i.e. responses to extreme events (Table 4). In some cases, to ensure accuracy of description, respondents demonstrated the activities and practices they employed. The age, gender, primary occupation and tribal or clan affiliations of the participants were also recorded.

Table 4: Summary of Interview guiding questions for the interviews and focus groups conducted in Konso, Ethiopia

Farming and Energetics
1. Do the participants own land within the village territory or outside of it? Where do they own land? a. Do they have more than one piece of land? If so, how many, are they all in the same place? And how far are they from the homestead? b. Do they farm all their pieces of land? If not, why did they choose not to cultivate some? c. Do they farm land other than their own? If so, is it in the same place(s)? Do they use it for the same thing(s) as their own land? 2. Have they stopped using some of their fields for farming? If so, when and why? 3. How many villagers have left the current area to farm in other areas? Do you

know why?

4. How long does it take the participants to move from the village to their piece of land or from one field to another? How long does it take to return?
5. What do they do if there are very heavy rains or very dry periods?
    a. Do the terraces and other walls usually survive very heavy rainfall events?
    b. How much do you have to rebuild the terrace walls each year due to rainfall damage?
6. What activities do they undertake during each part of the agricultural cycle and how much time and labour do they allocate to each? Do the activities vary between the different seasons and why? Who carries out these different activities?

Seasons: a) Bona (December to February; Dry season); b) Katana/ Sorora (February to June; Long rains); c) Masana (July to September; Dry season) and d)Hakayta (October to mid-December; Short rains)

Activities:

a. Before the long rains?
b. When preparing the fields?
c. When planting and weeding fields?
d. When harvesting?
e. After harvesting?

7. How do they allocate time and labour for the different activities? (Follow up if no clear response: e.g. continuously or in intervals?) What different things do they do to allow them to carry out more strenuous activities in the field? (E.g. to follow up – beer for work parties etc.)
8. Do different crops have different time, resource and labour needs?
    a. Do they grow different crops on different farms or during the different parts of the agricultural cycle? If so, which and why?
    b. Do they grow different crops in the terraces and the yelas or on different soils? If so, which and why?

c. Do they plant more crops during the long or short rainy seasons? If so, why?

d. Do they apply manure or ash to their fields? Does this differ between the terraces, yelas and village gardens? What are their reasons?

e. Do they practice fallowing, intercropping or crop rotation? What are their reasons?

9. Do they have different activities that they follow at different times of the day i.e. in the morning and in the afternoon?

   a. Schedules of what they do in the morning, lunch, afternoon and evening during the different seasons.

10. During the growing season, how much time do they spend on their different fields? How do they decide? (E.g. follow up: Is this dependent on how much yield they get or anticipate getting?)

11. What is the division of labour in farming and terrace construction and maintenance? Use of group working?

12. What is the construction and maintenance process for the hill-slope terraces? Yelas? Kabas (irrigation canals that direct water into the Yelas)?

   a. What do they usually do and to maintain the terraces, kabas yelas? And which period do you carry out these activities?

   b. How many people and/or how much time does it take to build or repair a damaged terrace, Yela or Kaba?

Terrace history, construction and maintenance

1. Have the terraces and yela fields always been on the participant's land? Were they in use throughout their lifetime? Can they estimate how long they have held the land in their family?

2. Do they still use the terraces and Yelas?

   a. If they still use terraces and Yelas, why do they do so? What are the advantages and disadvantages of using the terraces (and Yelas)?

b. If they stopped using the fields or terraces and yelas, when did they stop using them and why did they do so?

c. Did they stop using the terraces and yelas at the same time or in sections and why?

d. Do they continue to maintain the terraces even though they are not in use?

3. Are there different types of terraces? How and why are they different? (E.g. follow up- how do you decide how wide a terrace should be/how tall the walls should be?)
4. Have the walls/courses of the terraces or yelas been raised or added to? If so, how much effort does it take?
5. What is the process for water offtake when using the Kabas? Who decides and how do they decide who gets the water? Is there a schedule for offtake or is it as per the farmer's discretion? Who decides who gets water?

2.6.2 Thematic Analysis

The data from the respondents were anonymised using a coding system to protect the identities of the respondents. In addition, the anonymization system was also used as an identifier when discussing the findings. The data were then analysed for the emerging themes following grounded theory using the Glaserian approach (Alasuutari *et al.* 2008, 470-473; Heath and Cowley 2004; Glaser 1998). This approach involved preliminary scanning of the responses and then the development of initial codes and themes that emerged from the data as well as based on pre-existing literature. These initial codes were then further scrutinised and selective codes developed; the codes developed were supported with memos that expound on the underlying themes and categories. These codes were then categorised into themes and assessed to determine the overarching themes.

2.6.3 Findings

The overview of findings for each of the case studies is outlined below, and the themes emerging from the study are discussed further below. The total number of female respondents in both studies made up 46% of respondents while male respondent made up 54% (Table 5). The interviews in Engaruka comprised of 4 women and 6 men, while in Konso the interview respondents were equally dividedbetween the genders i.e. 3 men and 3 women. In Konso, each focus group was made up of respondents from the same village with one focus group of five women and men from *Kuile* village while the other focus group of six men and five women was from *Geldime* village.

Table 5: Number and Gender of respondents in the qualitative study

Study	Female	Male	Total
Engaruka, Tanzania - Interviews	4	6	10
Konso, Ethiopia - Interviews	3	3	6
Konso, Ethiopia – Focus Groups	10	11	21
Total			37

2.6.3.1 Case study: Engaruka

Discussions and interviews found that the Engaruka community has an intricate irrigation and water-allocation system that relies primarily on the Engaruka River as the water source. The area is divided into two major regions of Engaruka Juu and Engaruka Chini where each region is allocated 12 hours per day of access to the water. Further, Engaruka Juu, is subdivided into seven smaller villages where each village is allocated water on a rota of 3 or 4 days. This means that typically, access to water for irrigation occurs every 21 days for a given farm. In addition, farmers growing vegetables/horticultural crops such as onions and Chinese cabbage were allowed one hour of water access every day. The irrigation practices employed by the Engaruka community are seen to be a response to the local environmental conditions. A majority of respondents identify as predominantly pastoralist and farming is seen as a means of providing an additional food source and income. The enforcement of *Ujamaa* system in the 1970s resulted in the forced settlement of the migratory communities of the Maasai and Somali in the Engaruka area which also played a role in encouraging the uptake of farming. The low rainfall experienced in the region is likely to have played a role in the development of the irrigation system employed by the communities.

Irrigation Practices

The irrigation protocols employed by the participants, prior to water allocation, involve clearing debris in any feeder irrigation channels within the farms as well as tilling of the soils and bolstering the contours. The contours allowed the water to be trapped within the farms and allow for the water to infiltrate into the soils. The reasoning behind this was noted as primarily to prevent soil erosion with some respondents saying that they "build contours at the far end of their farms to prevent the water from just running through and carrying away the soil". Other participants noted that the contours trapped water and allowed it to infiltrate slowly into the soils, maintaining soil moisture for longer. This points to respondents understanding of soil and water conservation and provides insight in to the possible decision-making processes involved in the management of their irrigation system. If we relate this to the historical Engaruka system we can see how the need to conserve water and improve soil moisture as well as prevent soil erosion could have played an important role in the historical communities' decision to employ stone-bound sediment trap fields for soil and water conservation.

Water access within the community studied has a great influence on the crop productivity some respondents stating that "the allocation system affects the crops grown and the planting schedule as one must wait for water access". As mentioned above, the water-allocation rota means that each village receives water every 3 or 4 days with individual farms receiving water approximately once every 21 days. While the farmers were able to rely on receiving a consistent supply of water, the adequacy of the water received would have a bearing on the farmers' management of their farms. The farmers all felt that they were not receiving adequate supplies of water as they were limited to approximately 2 hours of access for their farms. In eight of the ten cases, the respondents employed a variety of strategies to cope with the water availability. Most farmers would grow crops that were able to tolerate drier conditions such as maize and black beans. Another strategy was to grow commercially desirable vegetables such as Chinese cabbage, spinach and kale on small portions of their farms. These vegetables which require more water, would allow the individual farmers to request for additional water access, increasing their allocation. The farmers had to work within the constraints of the water allocation and scheduling system to ensure viable crop productivity. This response ties to the understanding of how water-allocation within the historical Engaruka system could have functioned as well as the effect of this water-scheduling on crop choices and labour allocation to different farms.

The assertion that the water-allocation system was established by the community was supported by six of the ten respondents who identified the development of the water-allocation system as a community effort in order to try and ensure adequate provision and distribution of water resources across the farming area. This is important in understanding one of the ways in which the historical Engaruka water-management system could have functioned. There have been debates over the issue of centralised versus household/community organisation in water management with some studies arguing that the only way these systems could be managed would be through a centralised system. The respondents assertion that the system developed as a community effort points to a more collaborative structure in water management that could be limited to household or community level decision making as compared to a hierarchical or centralised system.

Soil Characterisation

The participants identified two main soil types in the Engaruka juu area as *Kichanga* (*Olrok* in Maasai) and *Tifutifu* (*Ar ng'arua* in Maasai) with *Kichanga* described as a dark soil that is gritty and free draining while *Tifutifu* was described as a red/brown soil that retains water better. The *Tifutifu* was also considered to be more fertile than the *Kichanga* soil. The participants also grow a wide variety of crops on the different soils with the majority cultivating maize and various legumes such as Black beans and Cowpeas as well as other crops such as bananas, potatoes and vegetables i.e. Chinese cabbage, onions, kale and tomatoes. The participants stated that the only crops that do well in the area were maize and black beans and the rest were not as productive and mainly grown for subsistence.

The respondents identified the influence of soil type on crop productivity, which has an important role to play in the management of this system. This is important in understanding the choices made by the farmers on the crops to grow based on the soils available and, as discussed below, the strategies employed to improve soil fertility and crop productivity.

Farming Practices

A majority of those interviewed i.e. nine of the ten respondents, would incorporate fertilisers into the soils in order to improve soil fertility and would mostly rely on manure from animal droppings and would rarely use commercial fertilisers. When questioned about this, nine of the respondents stated

> "……the commercial chemical fertilisers have to be added constantly to the soil to maintain fertility….."

One of the respondents felt that the commercial fertilisers were best for use in growing vegetables, but were too expensive for larger scale. Of the ten respondents, two utilised commercial fertilisers and noted that the fertilisers required repeated application; they thus preferred the use of animal manure to improve soil fertility. Nine of the participants would apply animal manure to their fields to improve soil fertility. This gives an idea of the possible choices of practices that could have been employed by the community to improve soil fertility. The farmers balance the cost of the inputs with the possible benefits that could be derived from their use. The farmers also adjusted their practices due to their own observations showing variability in decision-making over time. This can be exemplified by one of the respondents who did not utilise animal manure, while the respondent recognises the benefits, the labour inputs required to transport the manure to the field as well as time constraints meant that the they were unable to employ this strategy. In this case, the possible benefits of the inputs did not outweigh the labour costs required by the farmer.

Two of the ten participants practiced crop rotation or fallowing with one stating that

> "…..fallowing is only possible if you have big or many pieces of land….."

Crop rotation is also rarely practiced with intercropping more common. Intercropping would usually involve alternating growing seasons of maize only with maize and black beans. This is important in noting if the farmers employed measures to improve soil fertility such as fallowing, crop rotation or intercropping. The farmers would mainly rely on the use of animal manure in these cases because the farmers did not have adequate land to allow them to fallow some areas while still being able to produce enough for subsistence. The use of intercropping was utilised mainly to provide a variety of crops for subsistence and as a strategy to cope with climate and rainfall variability rather than for soil fertility.

Livestock are also used to clear post-harvest vegetation on farms, with most participants preferring to allow the animals to access the farm rather than stall feeding them. One of the participants noted "….most of the farmers here are pastoralists and their purpose for farming is mainly to provide fodder for their animals as well as for [supplementing] food…..". In this case the farmers utilised the post-harvest crop residues as important animal fodder, however they were not as concerned about the possible damage the livestock would cause to the fields. This is in contrast with four other farmers who would not allow livestock on their farms specifically to prevent damage to the earth bunds and irrigation canals. This is important in understanding the role of livestock within the communities, where some farmers prioritised their livestock while others prioritised their farms.

Overall, the modern Engaruka community employs not only community-level strategies for water-management but also individual farmer households employ strategies in response to their household-level circumstances.

2.6.3.2 Case study: Konso

The interview and focus group discussions found that the farmers in Konso employ a variety of coping strategies to deal with issues of labour, soil fertility, water variability and risk and uncertainty. The community members employ intricate reciprocal relationships, known as *paraka*, to mobilise labour for a variety of farming activities. In addition, the farmers employed other strategies for coping with situations where labour is limited, such as incremental repairs to more extreme cases where they left the hillslope terraces to fallow for extensive periods as well as demonstrating household strategies for dealing with situations where labour is limited. For example, when more extensive repairs are needed such as across an entire field, the household would request other members of the village to assist with repairs under the *pakara* system. Large groups would schedule a day for the repairs and the households would be obligated to provide food for the volunteers and reciprocate if any of the volunteers require assistance in future.

Farming and Energetics

Typically, the respondents scheduled different activities based on the different seasons. Activities in the dry seasons, mainly involved harvesting, hillslope terrace maintenance, alternative economic activities such as trade and land preparation. During the rainy seasons, the main activities included planting, weeding, and managing the irrigation canals (*kaba*s) for those who had *yelas*. The amount of time and energy varied for different activities with most respondents stating that terrace repair and maintenance, and planting requiring the most time and labour input. One of the reasons for the high labour demands for planting on the terraces was that ploughing with cattle could not be utilised on the terraces, therefore farmers would have to prepare the land using hand ploughs which would require two people typically to complete one row of terraces over a period of one day. The terraces required continuous repair with most respondents reporting that there would be damage to the terraces after every rainy season. One respondent noted that it would take one person between 4-6 days to repair a terrace wall approximately one metre high and approximately five metres long. However, the poor fertility of the terrace soils meant that the effort put into repairing and maintaining the terraces did not translate into good crop yields. The respondents noted that the yields from the terraces were not as good as that from the *yelas*, based on their comparisons of yields in the terraces and in the *yelas* from previous harvests.

The majority of the respondents would divide time and labour between their different fields if they had multiple farms, and would prioritise fields that they recognised as being the most productive based on the previous year's yields. The *yelas* were considered the most productive and those farmers owning *yelas* would prioritise maintenance of those fields over the hillslope terraces, with some farmers allowing the terraces to fallow or growing grass or trees on them for fodder or food. For the majority of farmers who rely on the terraces for crop production, the maintenance of the terrace walls would fall on household members with few able to afford the high cost of conducting a *pakara*, as the burden of feeding all the volunteer helpers would fall on the household. In addition, the household would have to reciprocate and provide assistance to the volunteers who came to their aid through the *pakara*, taking time away from their own farms. This means that while this technique is beneficial in mobilising labour for the repair and maintenance, there was a future cost in that the household would have to reciprocate. This would have a future cost of taking a large amount of time and labour away from their own farms, much higher as while they received one to two days of assistance on their fields, they would potentially lose more than those days on the different farms of the different households that had previously assisted them. This points to farmer decision-making on the cost-benefits of their choice in labour inputs. Selecting *pakara* would allow them to complete major repairs at a much faster rate, however they would lose time and labour that could have been focused on their farms in order to reciprocate. The costs to their own ability to maintain their farms and the potential effects on productivity would therefore be considered a risky choice of strategy by the farmers.

Terrace history, Construction and Maintenance

The majority of the respondents had farms in different places within the study areas, with some farms closer to the villages with others spread across the surrounding landscape based on historical land divisions as well as contemporary land tenure. Most respondent had both land on the terraced hillslopes as well as *yelas*, and expressed a preference for farming on the *yelas* as compared to the hillslope terraces. The majority of respondents explained that the reasons for this was the poor fertility of the hillslope terraces and the intensive labour requirements needed to maintain the terrace walls for effective agriculture. As discussed in the section on energetics above, the high labour requirements of the terraces did not necessarily result in improved crop production.

The majority of respondents have no memory of the original builders of the hillslope terraces or *yelas*. In addition, two out of the 27 respondents had extended or incorporated new terraces or *yelas* on their lands. One farmer who had extended a section of *yelas* on inheriting the land, and remembers their father working on sections of the walls for the *yelas*, and that the terraces and *yelas* had always been there "…from before my father's time…". Another farmer had extended the terraces and constructed new terraces on their land, which contradicts findings by Watson (2009) that found that the farmers did not build new terraces. However, this farmer falls under a minority as none of the other farmers interviewed had constructed new terraces on their land but would instead repair and maintain the existing terraces. The majority of respondents either inherited the lands from their parents or married into families that held terraced lands and/or *yelas*, with some purchasing more land or being allocated land under a new government project being conducted at Sagan River. This provides us with an understanding of the continuity of practices employed by the farmers, for example, the majority of farmers would continue maintaining the terraces on their fields even when they are left to fallow. In addition, the farmers are seen to employ strategies to cope with variability on crop production by having farms in different areas such that given different environmental conditions and labour requirements, the farmers could prioritise the fields that they believed would provide the best returns for their inputs.

2.7 Discussion

The different methodologies discussed above provide information on the topography, pattern of field terrace and irrigation infrastructure development, and management strategies that could have been employed in the historical Engaruka system. The results from the data were then used to support the development of the agent-based model of the historical Engaruka system which assesses patterns of development of these stone-bound fields and the sustainability of the system over time. The archaeological excavations conducted in 2014 found evidence that the field system in the south fields were constructed through sediment capture, with distinct similarities in how the sediment trap fields developed in the South fields and the North (Lang and Stump 2017). However, these fields in the North and South fields were distinct from those in the Central fields. In the South fields, deeply incised gullies showed evidence of deep deposits of sediments, which were similar to those found in excavations conducted by Stump (2006a) in the North fields. The topographic surveys mapped out the extent of agricultural fields and the evidence of archaeological features such as embankment walls. The data from these excavations was used to estimate the depth of sediments captured in the fields and together with the area of the study site, the volume of sediments captured was also estimated. The results of the aerial surveys provide additional information on the pattern of field construction and the placement of irrigation canals relative to the sediment trap fields. The results of the hydrological surveys along the Engaruka River, Olemelepo River and adjacent off-take canals found that water velocities within these channels ranged between 0.2 – 1.0 m s^{-1} and the total suspended sediment transported ranged from 100 -800 mg L^{-1}. The flow rates within the channels and the TSS values provide data to support modelling the flow velocities and discharge rates within the ABMs.

The results of the semi-structured interviews and focus groups found that the community in Engaruka relied on an intricate water-allocation system that relies primarily on the Engaruka River as the water source. The low rainfall experienced in the region played a role in the development of the irrigation system employed by the community. The majority of respondents identified as predominantly pastoralist with farming seen as a means of providing an additional food source and income. Famers would typically have access to water for irrigation every 21 days but farmers would employ strategies such as growing vegetables/horticultural crops which would increase their water access to one hour every day. The community in Konso also employed variety of coping strategies to deal with issues of labour, soil fertility, water variability and risk and uncertainty. The majority of the respondents would divide time and labour between their different fields if they had multiple farms, and would prioritise fields that they recognised as being the most productive based on the previous year's yields. The intensive labour required for the maintenance of the field terraces required farmers to employ a variety of strategies such as conducting incremental repairs as well as mobilising additional labour through the *paraka* system of reciprocal labour mobilisation. In addition, farmers would allow for long fallow periods on hillslope terraces where labour was limited or they had other more productive fields, but would still retain ownership of the fields by planting grasses for fodder or trees.

The data obtained from the excavations, hydrological and aerial surveys conducted in the south fields therefore support the modelling of water flows within channels and sediment capture in the stone-bound fields within the North fields based on the similarities noted. This means that by modelling how water flowed within these canals it is also possible to assess how much entrained sediments these flows could carry, and hence the minimum and maximum rates at which the stone-bound sediment trap fields and field terraces could have been constructed and expanded. Incorporating the decision-making strategies employed by the communities from the interviews and focus group studies, the model is able to provide insights into how the system function and how farmer decision-making allowed them to adapt to various circumstances overtime. By combining the data discussed above with established hydrological and sedimentological and behavioural theories, the models on the development of the Engaruka system would then support our understanding of the systems sustainability in terms of its ability to provide adequately for the community involved, and its ability to cope with extreme environmental changes.

Chapter 3 Engaruka Model Conceptualisation

3.1 Overview

This chapter discusses the model conceptualisation that outlines the factors that influenced the development of the Engaruka water-management system and their interactions in order to facilitate the design of the model structure for the agent-based models. The challenges and solutions to incorporating and modelling the different environmental and social factors at different social and temporal scales and degrees of complexity are discussed. The strategy for the development of two agent-based models is addressed and the model concept designs for each of the ABMs developed are outlined.

3.2 Model Conceptualisation

As outlined in Chapter One, the factors that influenced the development of the Engaruka water-management system include environmental factors of climate, topography and vegetation as well as human factors of population, social norms and decision-making in relation to farming. The extensive archaeological evidence available gives us information on the extent and complexity of the field system (Stump 2006a; Sutton 1998). However, this evidence presents only one aspect of our understanding of the system, but the factors behind its development and continued use, and ultimately if the interaction of these factors led to a sustainable system, are not clearly understood. The use of irrigation systems can be seen as an adaptation in response to changes in environmental or socioeconomic conditions, resulting in a more resilient society. However, there exists only the archaeological evidence of the system which does not provide all the necessary information needed to determine the resilience of the system.

Simulating the various environmental and socioeconomic scenarios that could have influenced the development of the Engaruka water-management system enhances our understanding of the factors that drove its continued use and provide possible reasons for the systems eventual abandonment. In doing so, the research aims to refine our understanding of the sustainability and resilience of the historical Engaruka system, as well as having applications in modern water management systems. However, the limited archaeological data presents challenges in modelling environmental factors and human behaviour that tie to how the system developed spatially and over time. In order to model the possible environmental processes involved, the rainfall-runoff dynamics, erosion and deposition processes, and the vegetation dynamics and sediment transport forces needs to be represented. However, the data inputs to characterise most of these factors have to come from environmental proxies, given that the system is believed to have been abandoned by the 19th century (Westerberg *et al.* 2010; Stump 2006a; Sutton 1998). Environmental records to assess the climate in Engaruka come from palaeoclimatic proxies such as sediment cores taken from the lakes and swamp within the East African region and analysed to determine the environmental conditions and timescales for the given climate events, as discussed in Chapter One. These environmental proxies present an opportunity to design an ABM that can incorporate simulations of the environmental processes most pertinent to the development of the Engaruka field system, and utilising the available evidence, to understand the development of the system. This ABM developed can be further expanded to incorporate human decision making.

The results of field studies as outlined in Chapter Two provide further information that can be used to model the system but this information is based on contemporary scenarios that may not necessarily reflect historical situations. The archaeological evidence of water management such as irrigation canals and agricultural terraces in the archaeological site of Engaruka provide an opportunity to explore the landscape level dynamics of the irrigation agriculture practices involved, in relation to the surrounding environmental conditions, by combining modelling and archaeological evidence. The hydrology of the agricultural landscape, with particular focus on study areas in the North and South fields are linked to other factors such as vegetation, climate, sedimentation rates, topography and human decision-making with the aim of understanding the reciprocal influences of these factors on each other in the context of the wider landscape, over a temporal scale; as well as the possible implications on the resilience of the Engaruka society. The model required to address the research problem needs to simulate past water management dynamics in a historical agricultural system, for which there exists no direct data such as hydrological measurements or ethnographic data. It is therefore necessary to design a model for the Engaruka field system that incorporates existing archaeological, hydrological, palaeoecological and qualitative information to simulate the development of the system.

3.2.1 Conceptual model of the Engaruka system

The conceptual model of the Engaruka system represents the environmental and human factors that could have interacted and influenced the development and sustained use of the system. In order to try to adequately facilitate our understanding of the Engaruka water-management system, the agent-based model developed needs to incorporate a range of interacting environmental processes and human factors as well as the archaeological evidence of the irrigation infrastructure. These factors include topography, vegetation dynamics, the climate (i.e. rainfall and temperature), hydrological dynamics and hydraulic dynamics of water and sediment transport as well as human factors involved in decision-making for agriculture, as outlined in the model conceptualisation (Figure 16). Each of the factors incorporate their own dynamics as well as interacting with other factors that result in the overall system dynamics that influenced the development and management of the Engaruka society.

As outlined in Figure 16, the climatic factors incorporate dynamics of rainfall and temperature interact to influence hydrological factors of infiltration, evapotranspiration and ultimately the soil moisture dynamics (Cai *et al.* 2015; Bronstert and Plate 1997). The climatic factors also influence surface runoff and recharge of water resources that affect sediment dynamics of channelised flow and sediment transport (Nu-Fang *et al.* 2011). The recharge of water resources in turn contribute to the hydrological and hydraulic dynamics of irrigation management. The hydrology, climate and sediment dynamic influence the vegetation dynamics (Scheiter and Higgins 2009, 2224) with water resources representing a limiting resource in semi-arid environments and irrigation hydraulic dynamics facilitating improved crop vegetation biomass in the face of unfavourable conditions (D'Onofrio *et al.* 2015; Oweis and Hachum 2006; Pereira *et al.* 2002; Critchley and Siegert 1991). In turn, vegetation dynamics affect sediment transport and hydrological dynamics of surface runoff and soil moisture recharge (Tietjen 2016, 13). The topography also affects the hydrology, irrigation hydraulics and sediment dynamics where the spatial distribution and patterns of water resources and topographical attributes such as slope affect the placement of the irrigation infrastructure (Harrower 2008, 502; Scarborough 1991, 102).

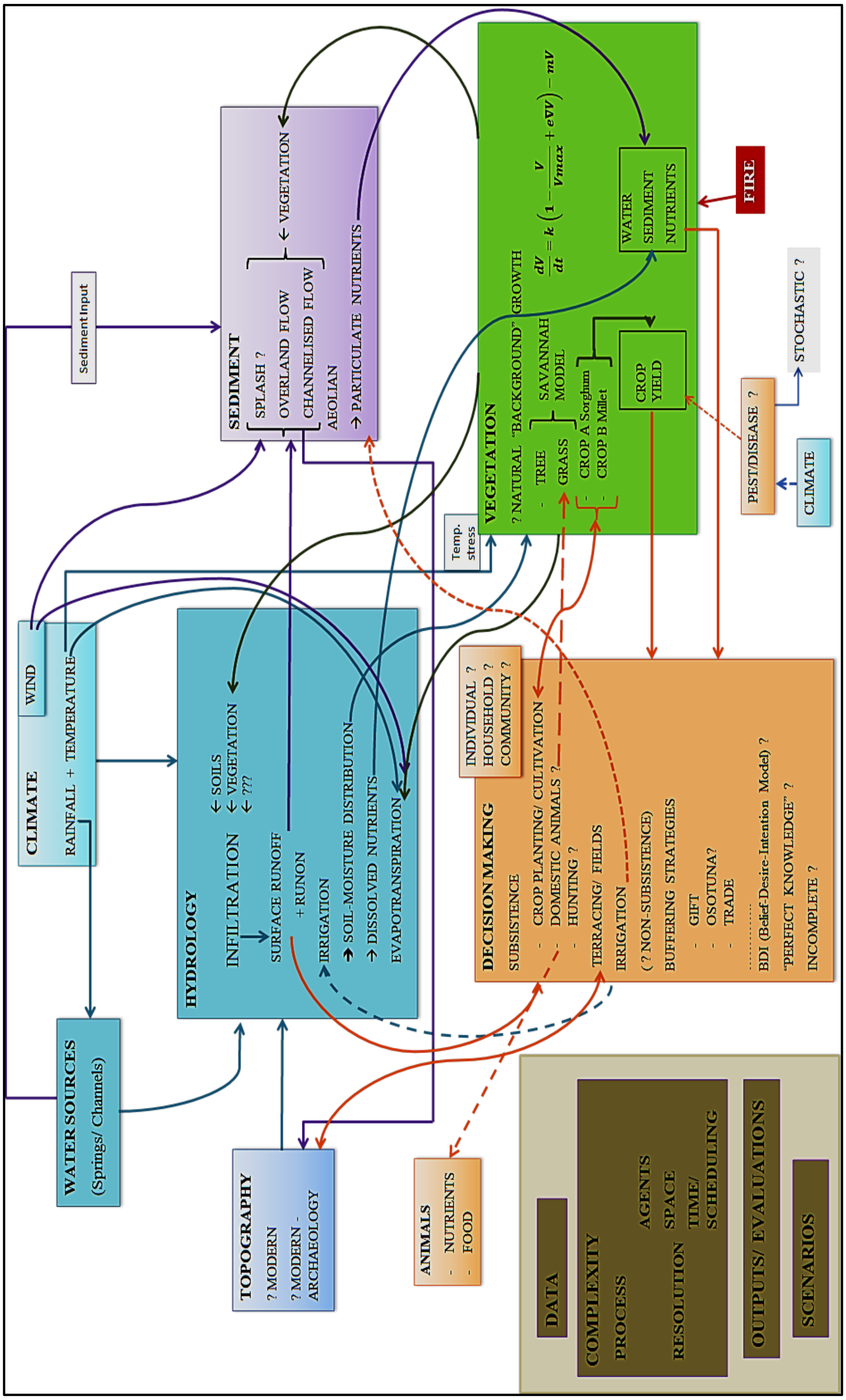

Figure 16: Model conceptualisation of the factors influencing the Engaruka water-management system outlining interactions that could have been integral to its development and continued use.

Interacting with all these environmental factors are the human dynamics for the management of the system where the farmers make decisions on subsistence agriculture and irrigation management in response to water resource availability and to improve crop yields. These factors influence farmers' decision-making and in turn the farmers' responses contribute to shaping their environment (Özerol and Bressers 2017, 46). The climate affects the farmers' decisions on agriculture and their adaptation responses while the influence of climate on the vegetation biomass affects the farmers' yields and thus affecting their decisions on the use of alternatives such as animals to supplement yields. The farmers awareness of changes in their environment thus affects their ability to adapt (Hassan and Nhemachena 2008, 93). However, the farmers do not have perfect information of the system and instead employ tactical responses to environmental changes (Risbey *et al.* 1999, 161). Decisions on where to farm are influenced by the topography as well as where to place irrigation infrastructure, and in turn the farmers modify the landscape to improve productivity (Harrower 2008, 502; Scarborough 1991, 102). The level of decision-making also influences the farmers' actions with decisions made at individual, household or community level influencing their actions where decisions at one level can constrain decisions at another (Groeneveld *et al.* 2017, 41). The farmer decision-making is guided by the belief-desire-intention model (Özerol and Bressers 2017) where decisions on farming, use of irrigation, response to climate change and other adaptation responses are made based on a combination of the resources available to them, their own expectation and social norms that guide decision-making. However, it can be difficult to determine how much of the farmer's knowledge is based on social or collective memory that has passed down through generations. This is particularly challenging when modelling decision-making in the historical Engaruka system as the modern community in the area, while providing analogous information on human responses to environmental factors within the same landscape, are not related to the historical community that previously occupied the landscape and developed the irrigation system. In addition studies by Minnis (2004) and Lane (1994) also highlight the possibility of loss or changes to collective memory that could result in novel practices or environmental adaptations being lost or changed. These aspects of social and collective memory would be difficult to infer from existing information and incorporate into the models. Thus the models allow for collective interactions but do notset out collective memory of environmental knowledge, and instead focus on practices and actions for which there is known history of its application in both modern and historical communities.

3.2.2 Challenges and solutions to Modelling the Engaruka system

The wide range of factors and dynamics conceptualised for the Engaruka system present a variety of challenges in developing an agent-based model that can effectively represent the system's dynamics and complexity. One of the main factors to take into consideration while developing the model is the issue of the level of complexity to be incorporated. While it is tempting to try and create a system that encompasses a wide range of factors, doing so could result in the incorporation of assumptions that might not adequately reflect the system being studied or provide useful outputs (Barreteau *et al.* 2004, 261; Wainwright and Mulligan 2004, 8; Holling 2001, 390). In addition, there are a wide range of pathways to complexity that might not be clear from the information available (An 2012, 25). One of the options for dealing with the incorporation of a wide variety of factors is through the use of coupled models. As discussed in Chapter One, there exist a variety of coupled models where one model incorporates the environmental, process-based simulations while the other model focuses on the agent decision-making. However such partially-coupled or fully-coupled models present a variety of challenges, such as intensive and extensive computational support, both in terms of software used and user technical skills, as well as having limitations in adapting scenarios (Castilla-Rho *et al.* 2015). A particular challenge faced in using partially-coupled systems is in their limitations in scenario adaptation, which require changes to the ABM as well as the hydrological model, in order to synchronise the codes between both simulation systems. This is particularly important when trying to account for different cultural and social behaviour, where there exist a wide range of human responses. Simplification of the model also takes into consideration the computational restrictions that affect runtime i.e. the amount of time it would take to run the model as well as the effect of large number of agents and processes that make simulation performance impractical due to high volumes of data outputs generated (Rhodes *et al.* 2016, 21). The approach employed here therefore incorporates the main processes that influence the system and focuses on building understanding of the system rather than creating a fully controlled system that hypothesises cause-and-effect. The aim of this research is therefore to develop an integrated agent-based model that incorporates both the environmental process-based factors with human factors expressed through agents that can interact with their environment while allowing for heuristic modelling of human decision-making. The model is simplified to allow for the main processes to be represented and produce useful outputs while allowing for interactions and adequate complexity in model structure.

The other factor taken into consideration in the development of an ABM of the historical Engaruka water-management system involves issues of scale, both temporal and spatial (Blöschl and Sivapalan 1995). The environmental and human factors that influenced the development of the historical Engaruka system range from spatial resolutions of 6×6 m fields to the wider catchment and landscape of the Engaruka system which covers approximately 20 km^2. In addition, the temporal scales for the different processes range from daily when looking at dynamics of sediment transport to monthly, decadal to centurial when looking at factors such as vegetation growth, crop management, decision-making involved in irrigation-agriculture water-management and overall sustainability of the system. The finer scales involved in sediment transport and canal hydraulic dynamics which operate at the field level and at daily or instantaneous time-steps present a challenge in incorporating into the longer term, landscape level processes involved in the wider system. The research presented here therefore developed two agent-based models of the Engaruka system that look at the effect of the different process at the different scales between the long term, wider landscape development of the Engaruka water-management system in contrast to the smaller field and canal hydraulic dynamics of the sediment transport and field system. The models developed are not coupled but these processes are tied through the overarching similar environmental factors of climate, topography and hydrology that have been adjusted to suit the different temporal spatial scales involved. While the models developed are not coupled and the outputs from one model do not feed into the other model, the models are related in their environmental factors of climate and variability in water availability that influence agent actions in both models. Taking the conceptual model outlined above (Figure 16), under the umbrella of environmental factors that are relevant to both models, the processes central to each of the research questions to be addressed are then developed into two distinct models. The outputs from both models are then combined in order to guide our understanding of the system at different temporal and spatial resolutions. In this way, the outputs from the models can then be integrated and assessed to further understand the Engaruka system as well as supporting assessments of other contemporary systems.

3.3 Model Development

3.3.1 ESTRaP Model

The Engaruka Sediment Transport and Capture (ESTRaP) model addresses the finer scale issues of sediment transport within a section of the field system. The influx of water and sediment discharge into the fields influences soil depth and fertility. The accumulation of sediments in the fields is a defining aspect of the Engaruka field system and understanding the timescales for the accumulation is one of the problems addressed.

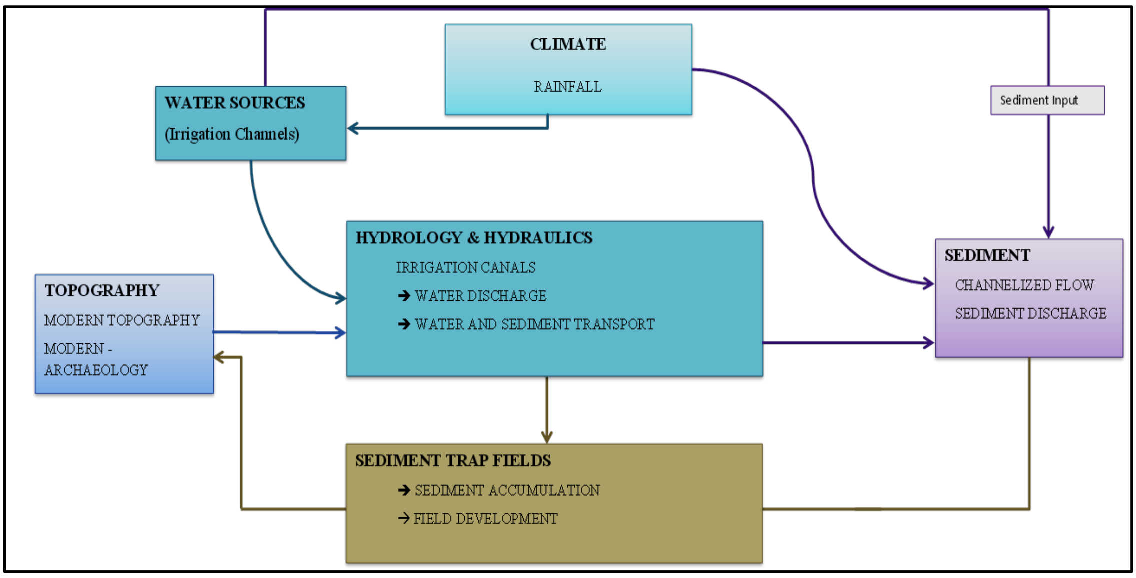

Figure 17: The concept diagram of the ESTRaP model outlines the structure of the model simulation; incorporating climate, hydrology and irrigation hydraulics, sediment transport dynamics, irrigation canal networks and sediment accumulation processes within a landscape characterised by topography.

As outlined in Figure 17 above (and discussed further in Chapter Four) the climate through rainfall affects the hydrology and water resources available in the irrigation canals. The hydraulic dynamics of the network of irrigation canals then facilitate the movement and transport of water and sediments within the irrigation canal system and distribution within the stone-bound sediment trap fields. The transport of sediments ties closely with the flow rate of water within the channels. The network of canals distributes the sediments to the block of fields modelled where they accumulate over time. The accumulation of sediments can then be related to the topography and the evidence of the modern archaeology found in Engaruka.

3.3.2 TIME-MACHINE Model

The Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME-MACHINE) model focuses on the landscape scale dynamics that led to the development of the Engarukan system, incorporating the environmental and human factors that influenced the development and continued use of the system. The wider landscape scale interactions of the society with the environment such as the influence of the changes in soil moisture and precipitation on crop yields, and farmer decisions to either plant more fields or use irrigation to extend the growing seasons have been explored by the second model. The model incorporates systems complexity by combining temporal and spatial scale-dependent biophysical processes and dynamics with human agent interactions (Asseng *et al.* 2010, 813). This model explores the use of irrigation agriculture and the influence of social norms on the resilience and sustainability of the system.

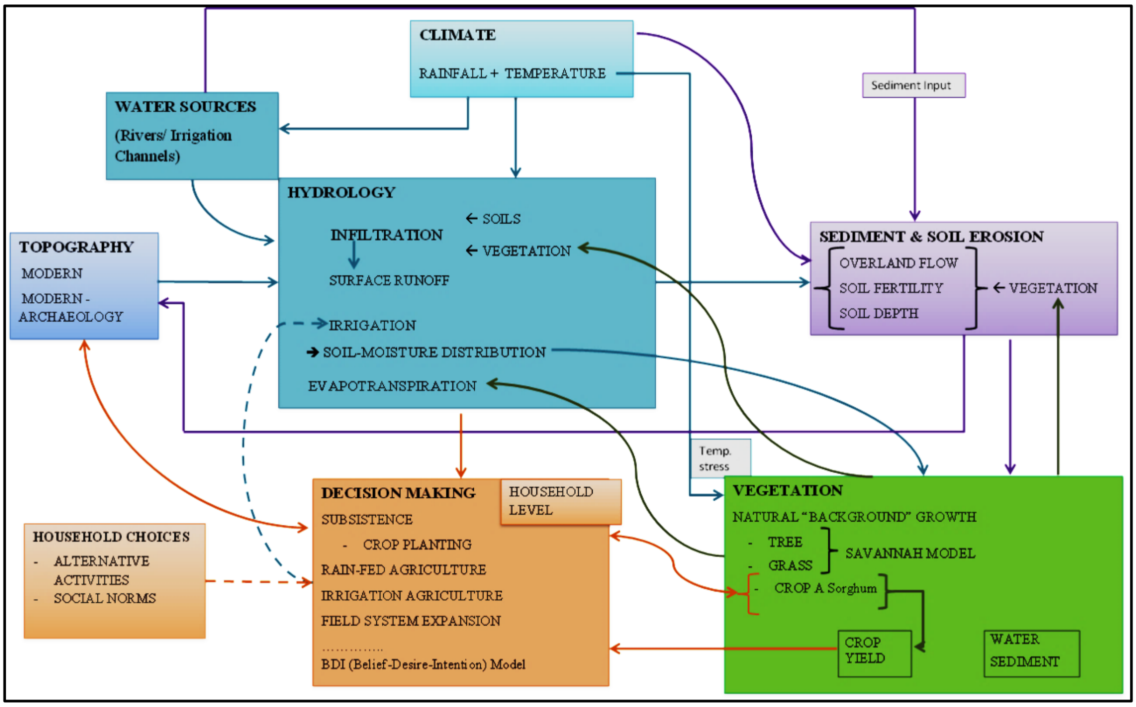

Figure 18: The TIME-MACHINE model concept diagram outlines the structure of the model simulation; incorporating climate, hydrology, soil erosion and sediment effects, vegetation dynamics, farmer household decision making and scenarios that influence the household choices within a landscape characterised by topography.

As outlined in Figure 18 above (and discussed further in Chapter Five) the climate, through rainfall and temperature affect infiltration and evapotranspiration which in turn affect soil moisture, surface runoff and soil erosion across the landscape. The soil moisture further affects vegetation dynamics through availability for plant growth while vegetation cover influences evapotranspiration and soil erosion. The sediments and soil erosion affect soil fertility which in turn has an effect on plant growth. The hydrological and crop vegetation dynamics influence the farmer households where decisions involving the use of rain-fed vs irrigated agriculture and the choice to incorporate alternative activities are governed by social norms. There exist a wide variety of human behaviour models to guide simulation of decision-making (see section 1.4.2). The The TIME-MACHINE model is guided by the BDI behavioural models (Özerol and Bressers 2017) (see section 5.2.2.2), which allows for the incorporation of the social norms and beliefs of the farmers as well as motivation and the limitations on their intentions placed by resource availability, and ties well to the ethnographic information collected from analogous communities.

3.4 Summary

The design and implementation of two ABMs therefore facilitates the exploration of the factors that influenced the development of the historic Engaruka system at the different spatial and temporal scales. This circumvents some of the computational issues that constrain modelling in NetLogo while enabling users to utilise similar scenarios across both models. Scenarios of water availability and climate change can be incorporated at similar scales in both models with the ESTRaP model focused on processes at a finer spatial and temporal scale while the TIME-MACHINE model focuses at the landscape level. Both models incorporate scenarios to explore the possible ways the system developed and how this relates to the archaeological evidence found today. In particular the models explore current factors such as climate change to assess the strategies the human agents employed and thus are able to relate them to modern-day water-management systems. The outcomes from the implementation of the different scenarios provide insights into the factors that influenced the development and continued use of the system. In addition the emerging patterns from the models and the performance of the models in simulating real-world scenarios as well as developing realistic outcomes is discussed. In this way, the models can support our understanding of the sustainability of the system and the application of the lessons learnt to contemporary systems.

Chapter 4 Engaruka Sediment Transport and Capture (ESTRaP) Model

4.1 Overview

This chapter presents the Engaruka Sediment Transport and Capture (ESTRaP) agent-based model which addresses the effect of water and sediment transport on sediment accumulation on a block of fields within the North Fields section of the Engaruka field system. The problem that the model addresses is discussed and the purpose of the model is outlined. Model assumptions are discussed to outline what the model does and does not address. The parameters central to the development of these models are explained and data sources for these parameters outlined. The scenarios that influence water availability that form the model simulations are outlined. The scenarios implemented in the models and the results of the analyses conducted are then discussed. The interpretations of model outcomes are discussed and related to existing literature, and the impacts of these interpretations on our understanding of the Engarukan water management system are summarised.

4.2 ESTRaP Model Design and Development

The construction of artificial sediment traps to create agricultural fields is a widespread practice in the modern world (Mekonnen *et al.* 2015), and is a practice that is increasingly being recognised on archaeological sites. These include long-abandoned sites like Petra in Jordon (Beckers *et al.* 2013), as well as ones in areas that continue to be farmed using techniques developed centuries earlier (Ferro-Vázquez *et al.* 2017; Hill and Woodland 2003). These also include landscapes where sediment traps are rarely if ever built today but act as exploitable legacies from previous periods of agricultural expansion or intensification (Giráldez *et al.* 1988). The drystone-bound agricultural fields that form the sediment traps, which are also referred to as check dams in some of the literature (Beckers *et al.* 2013; Abedini *et al.* 2012; Hill and Woodland 2003), can be built in a variety of ways and can perform one or more of several functions. It should be noted that the description of check dams in archaeological study should not be confused with those described in hydrological studies where the check dams are structures built to control sediment movement through ephemeral channels. The functions of these sediment traps include mitigating the impacts of soil erosion (i.e. by capturing sediments lost from the hillslopes, and thereby reducing the effect of sediment flows downstream), stabilising sedimentation, increasing soil depth and soil-water storage capacity, reducing runoff or the velocity of channelled water, accumulating fine sediments for ease of tillage or root penetration, or to create flat areas for cultivation within valleys or at the base the slopes (Mekonnen *et al.* 2015; Abedini *et al.* 2012; Ran *et al.* 2008). Within the archaeological literature such structures are also sometimes classified as a form of runoff agriculture or as a runoff terrace system (Beckers *et al.* 2013; Evenari *et al.* 1982), reflecting the fact that water harvesting systems can unintentionally accumulate the sediments entrained within water flows, most obviously in the case of the infilling of artificial reservoirs (Morrison 2015).

In the case of the archaeological site outlined here, it seems clear that the famers who built the irrigated-agriculture field system at Engaruka between the 15th and 18th centuries CE (Westerberg *et al.* 2010) intended to exploit available river flows while capturing the sediments these carried, in the process creating c.9 km^2 of sediment traps of between 350 mm and up to 700 mm deep in the northern end of the site (Stump 2006a), and accumulating sediments over 2 m deep towards the southern end of the field system (Lang and Stump 2017). Excavations and field surveys conducted in the South Fields in 2014 yielded provisional single grain Quartz optically stimulated luminescence (OSL) dates from between 700 ± 120 CE to 1860 ± 110 CE, which fall within the time period within which the Engaruka system was believed to be in use. In addition, stratigraphic and geoarchaeological studies conducted by Lang and Stump (2017, 10) found no evidence of erosion and breaks in sediment accumulation to the fields during these time-periods. In addition, the use of stone-bound fields would have minimised erosive processes of surface runoff, thus pointing to limited removal of sediments. The archaeological evidence of the historical field system also shows no sequences of abandonment or non-preservation of the field walls that would relate to contraction of the field system and discerning patterns of contraction in the archaeology would be difficult. It should be noted that in the modern Engaruka that abuts onto the historical archaeological site, the modern society also employs irrigation agriculture (Caretta 2015; Westerberg *et al.* 2010) which shows diachronic contraction and expansion of the modern field system (Figure 19). However it would be difficult to account for this field contraction and expansion in the historical system as the archaeological record shows no evidence of these contractions; the sediment transport model developed here therefore focuses on the expansion of the field system.

Although studies of archaeological stratigraphy can define the depth and extent of sediment accumulation, and can demonstrate broadly the sequence of sediment trap construction, this approach provides little data on rates of sedimentation, and hence the rate, pattern and manner of development of the system. The Engaruka Sediment Transport and Capture (ESTRaP) model uses a simulated version of part of this landscape with Agent-Based modelling (ABM) techniques in the NetLogo platform to address these issues, employing data from modern irrigation at Engaruka and palaeoclimatic data from the region (Ryner *et al.* 2008; Verschuren *et al.* 2000) to simulate different hydrologic scenarios. The techniques employed have the potential to contribute to studies of the efficacy and sustainability of sediment trap systems in the modern world by providing information on the accumulation of sediments over centuries, rather than simply over the few years available to modern observational studies (Barton, 2015).

4.2.1 ESTRaP Model Overview/Problem

The archaeological site of Engaruka in Tanzania offers an example of the utilisation of water and sediment transport to develop an extensive and intensive agricultural field system (Figure 20). The historical Engaruka irrigation-agriculture water-management system believed to be in operation during the 15th to the 18th centuries CE, covers approximately 20km^2 and comprises an extensive system of irrigation channels, stone-bound fields and agricultural terraces (Westerberg *et al.* 2010; Stump 2006a). The ESTRaP ABM developed therefore aims:

- To understand the overall effect of hydrologic and sedimentary dynamics on sediment accumulation in a series of fields within the North Fields section of the Engaruka field system.

In the study of water-management systems, particularly irrigation-agriculture, the role and effect of sediments transported within these systems can be positive or negative. In some cases, the sediments are viewed as an unwelcome but unavoidable by-product of the diversion of water resources. In other cases, these transported sediments are employed and deliberately accumulated within agricultural fields for a variety of reasons ranging from the perceived nutrient-rich qualities of clays which hold more organic matter, to the ease of tilling the finer sediments, to the influence of sediment particle-size on drainage, to supporting the construction, maintenance or expansion of agricultural soils and fields through the reduction of slope. By modelling how water flowed through the irrigation channels, it is possible to assess how much entrained sediments could also be transported and therefore extrapolate the amount of sediment that can be accumulated and the rates at which these stone-bound fields could be constructed and expanded over time.

The historical Engaruka field system comprised of a series of five rivers Engaruka River, Olemelepo River, Makuyuni River, Lolchoro River and the Intermediate gorge River which have their sources in the highland regions (Figure 19) (Westerberg *et al.* 2010; Sutton 1998). These rivers were diverted for the irrigation system into the fields through a series of canals. The stone-bound irrigation off-take canals extended into the fields with further tributary canals distributing water throughout the stone-bound fields and terraces (Stump 2006a). The main irrigation off-takes were on the perennial river of Engaruka, and the now ephemeral rivers of Olemelepo and Intermediate gorge; but apart from Engaruka, these other river sources have dried up (Westerberg *et al.* 2010; Stump 2006a; Sutton 1998). The modern Engaruka community that now lives within the extents of the historic system also utilises some of the remaining river sources and canals for irrigation agriculture but not to the extent evidence by the archaeology of the historical society (Westerberg *et al.* 2010). As mentioned in section 4.2 above, the modern landscape shows transitions from drier to humid zones due to the variability in proximity of the fields to water sources. However, the modern system is reliant primarily on water resources from the Engaruka while the historical system functioned during much wetter climatic conditions and employed a much wider network of irrigation canals and river resources which would have resulted in more water available for irrigation. The model developed therefore does not incorporate this variability and focuses on the expansion in the construction and development of the field system.

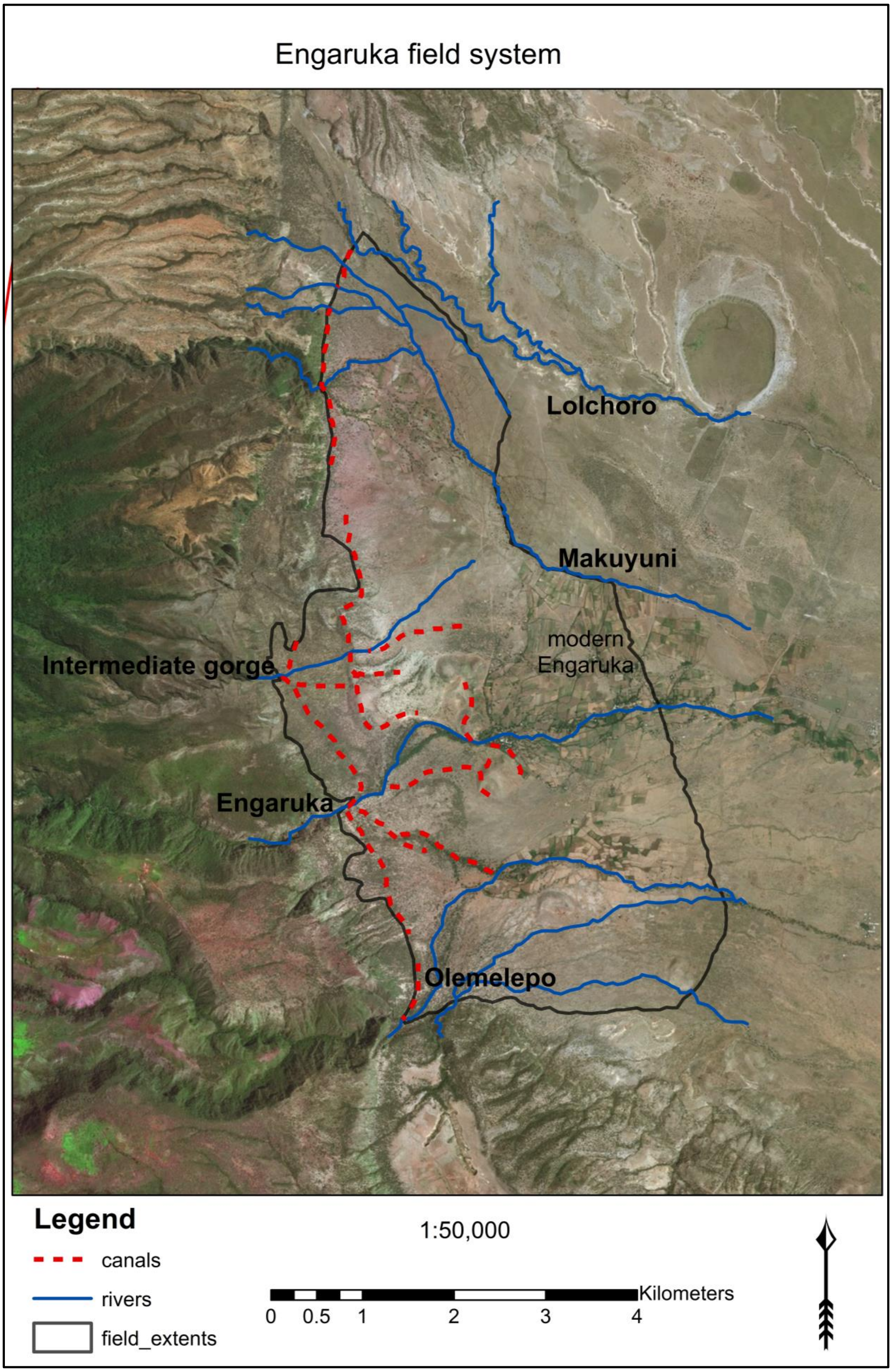

Figure 19: Location of the Engaruka field system, modern Engaruka settlement, network of rivers (blue) and the historical irrigation canal system (red dashed line)

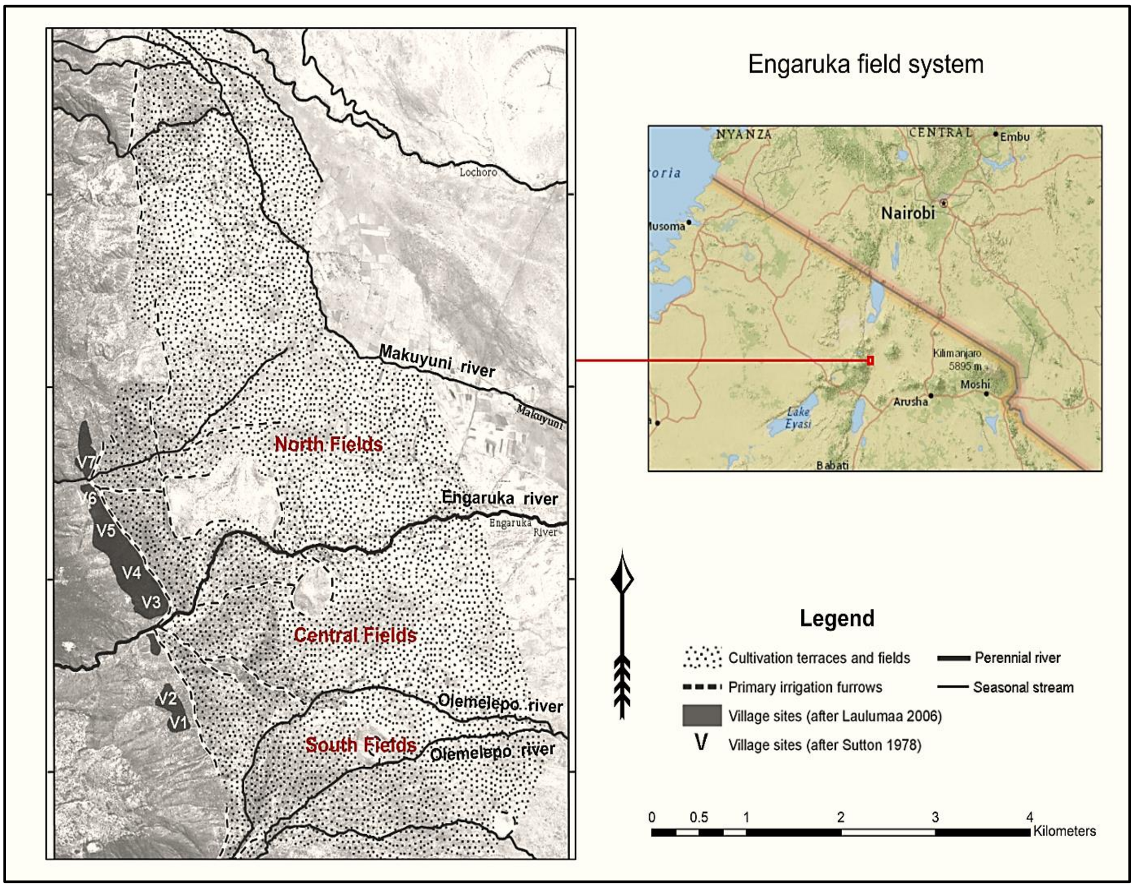

Figure 20: Location of the Engarukan water-management system and extent of the agricultural field system with river sources and village settlements.

Source: National Geographic World Map (Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC)

Across the 20 km^2 field system in Engaruka there are evident differences in the structure and function of the field divisions resulting in the field system being categorised into three distinct sections of the North, Central and South Fields (Sutton 1998). These distinct sections are defined based on differences in field construction, with excavations in the North Fields demonstrating that the fields were constructed through the periodic capture of sediments that were transported within the water channels and irrigation canals (Stump 2006a). Large parts of the South Fields were also developed through sediment capture and accumulation, similar to the North Fields, but on a much grander scale (Lang and Stump 2017), while the Central fields were built by tilling the existing topsoil and removing stones from the field area (Stump 2006a). Detailed stratigraphic excavations conducted by Stump (2006a) and a combination of stratigraphy, geochemistry and soil micromorphology studies by Lang and Stump (2017), have demonstrated how sediments were accumulated. However, the processes and interacting factors that could have resulted in the development of these fields are still not clearly understood. This is because subtly different processes and sequences of field construction could produce the same end result, and there is thus an issue of equifinality with respect to archaeological data. For example, the farmers could have utilised low flows from water diverted from the rivers into irrigation channels to transport and accumulate sediments in small field sections, or used much higher flows to flood larger areas and accumulate sediments more quickly. The multitude of interacting hydrological and sedimentary factors that could influence the construction and patterns of development of the field systems requires methods that can overcome the limitations of the existing data and interpretations. One such approach is the use of ABM techniques to allow for the exploration of the different scenarios that would result in the formation of the Engarukan field system.

Archaeological excavations conducted by Stump (2006a) in parts of the North Fields found that fields were constructed by creating drystone-bound fields of six by six metres along canalised streams with the first field set upslope of the stream (Figure 21).

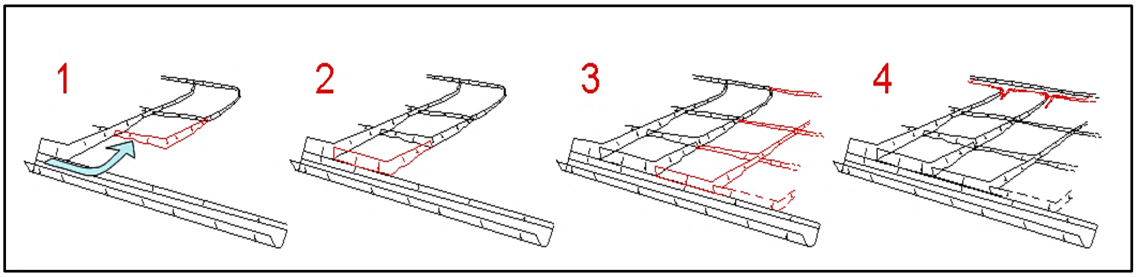

Figure 21: Phases of field construction based on excavations of part of the North Fields (Stump 2006a)

As shown in Figure 21, the phases of field construction based on archaeological excavations show field construction upslope of the canalised stream and travelling downslope towards the stream with consecutive fields constructed downstream along the canalised stream stump (Stump 2006a). In addition, an irrigation canal is constructed along the upper section to allow for water diversion into the stone-bound fields. During stage one and two, fields are constructed with the most upslope drystone-bound field first followed by another field set downslope of the first and towards the canalised stream. A further stone-bound field that abuts the canalised stream completes the first segment of fields. This process is then repeated along the stream with an irrigation canal incorporated at the uppermost fields as the fields are constructed. Observations by Stump (2006a) found that this irrigation canal was included as part of the construction of the field system and not a later addition. The pattern of field development identified through excavations points towards periodic sediment capture. However, the stratigraphic evidence cannot tell us the rate at which these fields were constructed over time or the hydrological and sedimentary dynamics involved. The use of ABM would therefore provide much needed information that strengthens archaeological interpretations and our understanding of the development and expansion of the Engaruka system.

The aim of this study is to assess the effects of water- and sediment sediment-transport dynamics on sediment accumulation and field development within the historical Engarukan water-management system. Given the large volumes of sediment observed in the stone-bound fields in Engaruka, it is important to understand the temporal and spatial patterns for the transport and deposition of these sediments. The primary functions of hydrological models that focus on surface-water systems is defining the rainfall-runoff dynamics of a catchment or watershed, and simulations of stream or channel flows (Davie 2008; Beven 2001). In studying the Engaruka irrigation system, the dynamics of rainfall, sediment transport and channel flows are important; however, conventional hydrological models require data inputs that are not available for this system. This is because flow measurements cannot be accurately taken from long-abandoned watercourses and rainfall records do not exist for the region and period under study.

In order to model the possible hydrological processes involved in the Engaruka system, the rainfall-runoff dynamics, erosion and deposition processes, and the water flows and sediment transport forces, would need to be represented.

However, the data inputs to characterise most of these factors would have to come from proxies, given that the system is believed to have been abandoned by the 19th century (Westerberg *et al.* 2010; Stump 2006a; Sutton 1998). These include a combination of archaeological or palaeoenvironmental proxies or combination of proxies as well as estimates from the channel dimensions from excavation data. These include off-site records such as palaeoclimatic proxies derived from sediment cores taken from the lakes and swamps within the East African region and analysed to determine the climatic conditions and timescales for the given weather events (Westerberg *et al.* 2010; Ryner *et al.* 2008; Barker and Gasse 2003; Verschuren *et al.* 2000). While these records can provide an approximation of the climatic conditions experienced they cannot provide precise data on the rainfall and runoff generated during these time periods, making it difficult to utilise conventional hydrological models. For this reason the current modelling prioritises on-site archaeological evidence including information on channel dimensions and gradient, and particle size of accumulated deposits, in order to model flow rates, since relying on only one variable such as water-channel data or sediment volumes risks the development of circular arguments. Combining these data allows for the representation of a range of different flow rates constrained by the physical dimensions of the irrigation infrastructure, while allowing for the simulation of a wide range of possible sediment deposition rates and patterns based on different environmental conditions drawn from palaeoecological case-studies. Together, these proxies present an opportunity to design an ABM that can incorporate simulations of the hydrological processes most pertinent to the development of the Engaruka field system, thereby refining archaeological interpretations of how the Engaruka field system was built and used. The model developed can also be further expanded to incorporate more complex patterns of field construction as well as human decision-making.

4.2.1.1 Purpose

ESTRaP ABM was constructed to perform a series of simulations to understand the temporal and spatial patterns for the transport and accumulation of sediments within a section of the stone-bound fields in the Engarukan water-management system. Sediment transport is dependent on a number of factors including the amount of water available, discharge and amount of sediment load that can be transported by the waterway (Mouri *et al.* 2014, 267). This model focuses exclusively on the physical processes of sediment transport and accumulation within a section of the stone-bound fields. The model simulates water flows and sediment transport through a small section of the canal systems covering c. 3,000 m^2 block of fields in the North Fields section of the site in order to demonstrate the core features of sediment accumulation. The purpose of this model is to understand the influence of irrigation infrastructure and water diversion on the accumulation of sediments and development of a series of stone-bound fields in the North fields of the historical irrigation system in Engaruka, Tanzania.

The aim of this model is to determine the amount of water flows and sediments that would be required to develop a series of six by six metre stone-bound fields along a set of irrigation canals located in the North Fields section of the Engaruka field system (Sutton 1998). The model focuses on the hydrology of channel flows and sediment transportation and deposition processes to determine the amount of time it would take to develop a series of fields given idealised conditions for water flow and sediment transport and deposition.

The model is designed for researchers interested in assessing the temporal and spatial scales as well as the hydrologic and sedimentary processes involved in the development and modification of landscapes through sediment accumulation. This information would be of particular use to archaeologists to enable the understanding of the timescales involved in the development of stone-bound fields and field terraces through sediment transport by water. In addition, modern irrigation systems utilise similar sediment trapping strategies and the results of this model would help in understanding the management of such field systems.

The model description is based on the agent-based model description protocol and the updated ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006).

4.2.1.2 Model Assumptions

The ESTRaP model omits more complex landscape-scale elements: rainfall and surface runoff and erosive processes, as well as site-specific elements of bedload sediment transport. This is in order to focus on the simulation of water flows and sediment transport within a network of canals linking a block of fields in the North

Fields section of the site so as to demonstrate the core features of sediment accumulation.

The effects of rainfall and surface runoff on discharge rates are not simulated directly within the model but are simplified and represented by variability in water depth within the irrigation channels. The hydrological processes of rainfall and surface runoff influence the amount of water available within water courses. Studies conducted have shown that rainfall increases can lead to an increase in surface runoff which in turn contribute to water flows in channels and canals and can result in corresponding increases in water depth (Linard *et al.* 2009; Montgomery and Buffington 1998) resulting in increases in water discharge rates. Studies, particularly on storm events, have shown that rainfall increases can lead to an increase in surface runoff which in turn contribute to stream flows and can increase water discharge rates from water channels (Linard *et al.* 2009, 1). The influx of surface runoff into water courses can also result in a corresponding increase in water depth (Montgomery and Buffington 1998, 19) which can also be related to the corresponding increases in the water flows and discharge rates. Therefore in order to represent the influence of rainfall and surface runoff in the model the variations in water depth act as proxies. Variations in rainfall at a temporal scale were therefore represented by variations in water depth to show the influence of these variations on water discharge. In addition to using water depth as a proxy for rainfall levels, Manning's method and roughness coefficient is considered a reliable method for the estimation of discharge rates (Roy and Mistri 2013, 4; Benson and Dalrymple 1967). Thus using a combination of Manning's roughness coefficient and water depth, the water discharge from the water channels (both canalised stream and irrigation-canals) will be estimated in the model.

Erosive processes across the landscape are omitted and sediment inclusion is represented by the total suspended sediments in order to focus on sediments already present within the channels. The omission of erosive processes is also because the presence of the stone-bound fields across the landscape would act to limit surface runoff and erosion (Mekonnen *et al.* 2015; Lesschen *et al.* 2009), so we assume lateral inputs into the channel are several orders of magnitude lower than the transport of sediment in the channel, and can therefore be considered negligible as a first-order approximation. While the ESTRaP model does not explicitly represent erosive processes, variability in Total Suspended Sediments (TSS) can be related to erosion where increased erosion in upstream regions can be represented by increases in the TSS in water channels. However this is with the caveat that surface runoff does not necessarily result in increased erosion. As studies by Lesschen *et al*. (2009) and Hooke (2003) on hydrological connectivity have shown the links between runoff, erosion and sediment are not always clear cut as the soil type and vegetation also can influence runoff and erosion. In addition, the presence of stone-bound fields act to intercept runoff and act as sinks for sediments and runoff as well as acting as sediment traps (Mekonnen *et al.* 2015; Lesschen *et al.* 2009). This also acts to limit runoff and erosion across the landscape particularly on the agricultural lands. For this reason, the model focuses on TSS within the channels and not erosion and runoff across the landscape. Variability in TSS therefore acts as proxies for erosion from upstream regions for the combined mechanisms of erosion.

In addition, the transport of sediments ties closely with the flow rate of water within the channels as the fast moving water will transport larger pebbles while slower flow rates would transport silt, sand and clay, where clays have formed aggregates, (Miedema 2010; Sundborg 1956). Studies by Lang and Stump (2017) have shown that the sediments captured within the field system were predominantly clays which tend to be transported in suspension (Robert 2014, 72) making bedload transport processes negligible for this model. It should be noted that studies on suspended sediments have found that the relationship between suspended and bedload transportation is more nuanced (Parsons *et al.* 2015). Sediments are found to travel in a series of hops rather than in perpetual suspension such that the sediments are repeatedly deposited and then re-entrained into the flow. However, for clarity of discussion in relation to this research, this complex dynamic shall be simplified and explored on the assumption of suspended sediment transport. The small particle size of clay particles i.e. smaller than 0.1 mm not only influences the sediment transport process in the water column but relates also to the bulk density of the sediments. The clay particles and other fine sediments transported also have attendant bulk densities that would affect sediment accumulation processes. The bulk density varies based on the proportions of sand, silt and clay and the consolidation period (usually calculated to one year). The model therefore places limits on the bulk density values for the sediments modelled to those of silts and clays which range from 1.1 - 1.6 g/cm^3.

4.2.1.3 Entities, State Variables and Scales

The ESTRaP model is implemented in the NetLogo platform version 5.2.1 (Wilensky 1999) and the model description is based on the ABM description protocol and the updated ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006). It consists of a simulated landscape representing a small section of the North Fields at Engaruka covering approximately 56,000 m^2 of the c. 9 km^2 North Fields area of Engaruka (Figure 20). Using a georeferenced digital elevation model to build the model environment, the ASTER GDEM V2 (NASA_LP_DAAC 2011),was resampled from the original 30 m resolution to a resolution of 6 m to match the size of the stone-bound fields recorded from excavations within the North Fields (Stump 2006a). The agents within this landscape comprise the water flows and the sediments transported within a network of irrigation canals.

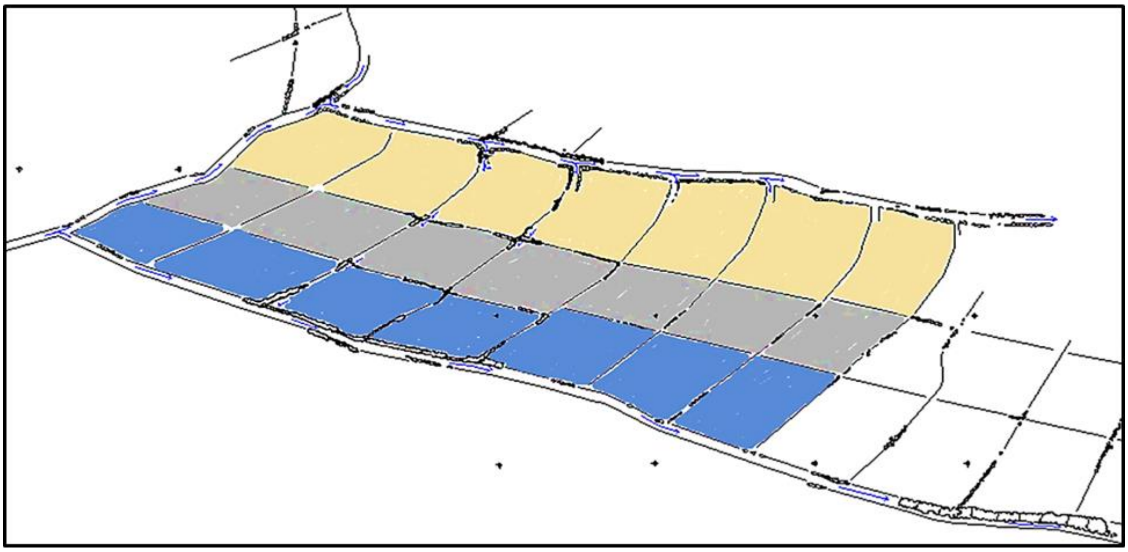

Figure 22: Visual representation of a block of sediment trap fields in the North Fields section of Engaruka used to simulate the field system in the ESTRaP model based on excavations conducted by Stump (2006a). The fields were constructed

consecutively from the upper fields (yellow) through the middle fields (grey) and down to the lower fields (blue), and from left to right (i.e. downslope).

In this implementation of the model a block of 90 individual stone-bound fields, were modelled to understand the timescales and pattern of sediment accumulation given simulated scenarios of different environmental conditions. Each fields has a 6 × 6 m resolution (Figure 22), and the 90 field block covers approximately 3,000 m^2 of the 56,000 m^2 of the simulated landscape. As shown in Figure 22, the block of fields was constructed between a canalised stream and an irrigation canal which directed water from the primary water source and into the stone-bound fields that acted as sediment traps. The model focuses exclusively on the hydrology of channel flows and sediment transportation and deposition processes to determine the amount of time it would take to develop a block of fields given different conditions for water flow and sediment transport and deposition.

Engaruka North-fields Habitat entities and variables

The Engaruka North Fields habitat is characterised by state variables of topography and slope. The habitat is represented by field patches characterised by soil depth and elevation. Each field patch has a spatial resolution of six metres by six metres in order to represent real-world measurements of field sizes of the system (see sections below). The fields and irrigation canals are characterised by location and elevation data with the canals further characterised by water velocity generated from analysis of canal dimensions from archaeological excavations. The primary drivers of this model environment are water velocity and suspended sediment volumes within the canalised streams and irrigation canals.

Temporal and spatial scales

The model runs on a daily time step with 365 steps making one calendar year, and with data on the amount of sediment accumulated and changes in soil depth collected at each time step. The model is spatially explicit, and the block of 90 fields simulated cover approximately 3,000 m^2 of the model landscape which covers a total spatial extent of approximately 56,000 m^2 of the North Fields based on a georeferenced DEM. The DEM used to model the landscape i.e. USGS EarthExplorer the ASTER GDEM V2 released in 2011 with a resolution of 30 metres (1 arc-second) (NASA_LP_DAAC 2011) was resampled to a resolution of 6 × 6 metres. The resolution of six metres by six metres was determined based on excavations of stone-bound fields conducted by Stump (2006a).

The main model parameters, variables and default values are described in Table 1 and sections below.

4.2.1.4 Process overview and Scheduling

The sediment deposition and accumulation process comprises four stages i.e. generation of water flows and sediments, water and sediment transport within the irrigation canals, sediment discharge in the fields and sediment accumulation over time. These processes occur within each year in the following order:

1. Water flows and sediment volumes are generated within the irrigation channels and modelled on the principles of continuous uniform open channel flows. The water flows and sediment volumes are distributed sequentially with the canalised stream receiving water first and then being distributed into the irrigation canals i.e. offtake canals and finally to the field offtake canals. In addition, the water distributed is divided amongst the total number of canalised stream and irrigation canals. In order to simulate water loss through seepage along the canalised stream and irrigation canals, a parameter of water loss is incorporated such that a certain proportion of the flows from the prior canal nodes are lost along the canals.
2. Water and sediments are transported within the irrigation canals with the water transporting suspended sediments. Similar to the water flows, some sediment would be deposited along the water channels if the flows are not fast enough and do not reach the fields. In order to simulate this phenomenon, sediment loss along the canals was incorporated into the model.
3. Water and sediments are discharged into the fields from the irrigation canals.
4. Sediments that have been discharged accumulate over time in the fields; with sediment accumulation a function of sediment discharge and bulk density and the inverse of a soil consolidation factor for soil compaction over time.

The total flows, sediment discharge and sediment depth for all the fields are collected at each time-step. The accumulation of sediments in the series of fields is calculated on a daily time-step and the results analysed to determine the amount of time required to accumulate the sediment depths that relate to the real world observations and archaeological observations.

4.2.2 ESTRaP Design concepts

The basic principles that were taken into account in the development of the model are presented below following the convention of the ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006).

4.2.2.1 Theoretical and Empirical background

The water flows, and sediment transport and deposition are modelled based on standard hydrological approaches including streamflow hydrology and sedimentation dynamics. The estimation of water discharge from the river channels and irrigation canals is based on the principles of open channel continuous flows for trapezoidal channels with Manning's roughness coefficient values within the range for natural streams with stone/pebble lined channels and excavated channels with rubble sides and earth bottom slope (Chow 1959) . The sediment discharge is estimated from a sediment rating curve, which is a linear relationship of water discharge and total suspended sediments; while sedimentation processes are based on the principles of sediment accumulation (Robert 2014; Wilkinson *et al.* 2006, 7; Gordon *et al.* 2004; van Rijn 1984).

4.2.2.2 Individual decision-making

There is no individual decision-making.

4.2.2.3 Learning

There is no individual or collective learning included in the decision model. The agents do not change the decision-making rules.

4.2.2.4 Individual sensing

There is no individual sensing.

4.2.2.5 Individual prediction

The model makes no predictions.

4.2.2.6 Interactions

The rate of water discharge has an effect on the discharge of sediments, with a direct linear relationship between water and sediment discharge.

4.2.2.7 Collectives

The model contains no collectives.

4.2.2.8 Heterogeneity

There is no heterogeneity of decision-making by the agents.

4.2.2.9 Stochasticity

The amount of sediment discharged varies with changes in water discharge which is in turn influenced by the water height within the river channels and irrigation canals. In addition, the amount of water discharge decreases with increase in distance from the main canalised stream.

4.2.2.10 Observation

The amount of sediments deposited within the fields is collected on a daily time step. In addition, the water and sediment discharge from the canals is observed. The amount of sediment that accumulates within each stone-bound field is observed over time and the amount of water flows through the channels and canals is also noted. The amount of time it takes for a field to accumulate sediments of up to 1 m in depth is recorded.

The data is compared between the varied environmental scenarios of seasonal variability in water availability and erosive processes i.e. as represented by changes in water depth in the canalised stream and variations in suspended sediments, to determine the influence of these variations on the rates of sediments transported, deposited and accumulated within the fields. In addition the data is used for sensitivity analysis to assess the model's ability to produce results highlighting the implications of these scenarios on the influence of the water diversion infrastructure on field development and sediment accumulation within the irrigation system.

4.2.2.11 Emergence

The key results emerging from the model are patterns of sediment accumulation and field development over time, given the different environmental scenarios of water availability.

4.2.3 ESTRaP Details

4.2.3.1 Implementation Details

The model is implemented in Windows 7 using the NETLOGO platform version 5.2.1 (Wilensky 1999). The source code can be made available upon request. The hydrological and sediment-transport model is implemented through agents consisting of a network of nodes and directional links to represent the irrigation channels that transport water and sediments to the fields. The nodes contain information on the flow and sediment discharges along the system of canalised stream and irrigation channels based on the agent characteristics. The directed links that represent the irrigation channels distribute water and sediments from the canalised stream into the fields via nodes set within each 6 x 6 m field. At each time-step (representing the passage of one day) each node shares a percentage of its value of sediments and water equally with its neighbours in the network of nodes. The nodes also retain a percentage of the sediments and water flows to represent sediment and diffusion loss incurred as these agents move along the network. The transfer of sediments and water flows terminates at the fields, where the nodes transfer these agents to the field patches as sediment discharge, which is then converted to represent sediment accumulation.

4.2.3.2 Initialisation

Initial conditions for state variables in each grid cell (elevation in metres above sea level, soil-depth in metres, and angle of slope) are derived from DEMs, archaeological excavations and surveys of the study site. The initial values for the water discharge and sediment discharge vary among simulations; however, some initial values have been determined based on existing data. Initial values such as water depth, used to determine cross sectional area of the channels and total suspended sediments (TSS), were based on data from hydrological studies conducted in 2015 along a 4 km^2 stretch of the Engaruka River as discussed in

Chapter Two. The irrigation channel dimensions were based on archaeological measurements from studies conducted by Stump in 2003 in the North Fields of the Engaruka field system (Stump 2006a). The model has four sub-models that represent the water and sediment discharge, irrigation canal networks and sediment accumulation. The model parameters, their dimensions and default values are described in Table 1 below.

4.2.3.3 Model Input

The elevation data for the model was obtained using a digital elevation model, the ASTER GDEM used is a product of METI and NASA (NASA_LP_DAAC 2011).

Table 6: Model Parameters, Variables and Initial values

Parameter	Explanation	Model initial/ default value
Water Transport and Discharge		
Q	Water discharge (m^3s^{-1})	> 0
k	Dimensionless constant	1
n	Manning's roughness coefficient	0.03
R	Hydraulic radius (m)	> 0
S	The slope of the channel (m m^{-1}) i.e. the height difference between the start and end of the channel over the horizontal distance of the channel	0.02
A	Cross-sectional area of the channel (m^2)	> 0
Sediment Transport and Discharge		
Q_s	Sediment discharge (tonnes day^{-1})	> 0
C_t	Daily total suspended sediment (mg L^{-1})	200

Parameter	Explanation	Model initial/ default value
Y	Conversion factor that converts m^3 s^{-1} to m^3 day^{-1} and mg L^{-1} to tonnes m^{-3}	0.0864
Canal Networks		
CN_jQ	Transport and distribution of water discharge in the network of irrigation canals	> 0
CN_jQ_s	Transport and distribution of sediment discharge in the network of irrigation canals	> 0
w_l	Water discharge loss along the canal network	> 0
d_l	Sediment discharge loss along the network	> 0
t_w	Proportion of water discharge that continues to be transported along the canal networks (%)	0.80
t_d	Proportion of sediment discharge that continues to be transported along the canal networks (%)	0.85
r	Number of irrigation canal recipients in the network	> 0
Sediment Accumulation		
ΔH_i	Depositional layer thickness (m)	> 0
$\Delta S_{tot,i}$	Total sediment volume in a given stone-bound field *i* (m^3 day^{-1})	> 0
f_i	Area of a given stone-bound field *i* (m^2)	36
$Q_{s,i}$	Sediment discharge within a given stone-bound field *i* (tonnes day^{-1})	> 0
BD	Bulk density of soils (1g cm^{-3} or 1000kg m^{-3})	1.10 – 1.60

Parameter	Explanation	Model initial/ default value
C	Consolidation/compaction rate of soils (days)	365

4.2.3.4 Submodels

Water Transport and Discharge

The irrigation hydraulics sub-model simulates the movement and transport of water and sediments within the irrigation canal system and water distribution within the stone-bound fields. The estimation of flow rates and discharge from the irrigation channels is based on Manning's equation for open-channel continuous flows for trapezoidal channels (Robert 2014, 31):

$$Q = \frac{k}{n} . R^{\frac{2}{3}} . \sqrt{S} . A$$

Equation 4

where Q represents water discharge (m^3s^{-1}) from the irrigation channels, k is a dimensionless constant, n is the Manning's roughness coefficient; R represents the Hydraulic radius (m); S represents the slope of the channel (m^1 m^{-1}), and A is the cross-sectional area of the channel (m^2). The water is then transported and distributed amongst the canals and fields. The dimensions of the canals are based on archaeological data from excavations conducted by Stump (2006a). The location of the irrigation canals and canalised stream within the model are spatially explicit and the water flows are diverted into the irrigation canals from the canalised stream. The amount of flow diverted into the field canals is a percentage of the total flows within the canalised stream. Amount of flows and sediments carried downstream within the canals or returned to the main river can be estimated. The nodes along the canal network contain information on the flow and sediment discharges along the system of canalised stream and irrigation canals. The field canal distributes water and sediments from the canalised stream into the fields.

Sediment Transport and Discharge

Sediments are transported by water in the irrigation channels, with the model focused on sediments transported in suspension and discharged into the fields based on the following relationship (Van Rijn 1993):

$$Q_s = Y \,.\, C_t \,.\, Q$$ Equation 5

Q_s represents sediment discharge (tonnes day^{-1}) into the fields. Q represents water discharge (m^3s^{-1}), C_t is the daily total suspended sediment (mg L^{-1}) and Y is a conversion factor that converts m^3s^{-1} to m^3day^{-1} and mgL^{-1} to tonnes m^{-3}. Sediment discharge is a function of water discharge and total suspended sediments. The transport of sediments ties closely with the flow rate of water within the channels as the fast moving water will transport larger pebbles while slower flow rates would transport silt, sand and clay (Miedema 2010; Sundborg 1956).

Canal Networks

The transport and distribution of water and sediment discharge is implemented through a network of links and nodes in the model to represent the irrigation canal system. The distribution of water and sediments through the networks is characterised by the number of canal recipients linked through the series of nodes and as water and sediments are transported along the network some does not reach the fields and is lost through seepage or deposition. Water loss through seepage along the irrigation canals is incorporated into the model and expressed as:

$$CN_jQ = \frac{Q - w_l}{r}$$ Equation 6

where:

$$w_l = Q.(1 - t_w)$$ Equation 7

CN_jQ represents water discharge (m^3s^{-1}) from a specified node j, Q represents water discharge (m^3s^{-1}), w_l represents water loss through seepage, r is the number of irrigation canal recipients and t_w (%) is the percentage proportion of water discharge that is transported. Water loss is a function of the water discharge and the proportion of water that continues to be transported in the irrigation canals.

Sediment loss due to deposition along the irrigation canals is expressed as:

$$CN_jQ_s = \frac{Q_s - d_l}{r}$$ Equation 8

where:

$$d_l = Q_s.(1 - t_d)$$ Equation 9

CN_jQ_s represents sediment discharge (tonnes day^{-1}) from a specified node j, Q_s represents sediment discharge (tonnes day^{-1}), d_l represents sediment loss through deposition, r is the number of irrigation canal recipients and t_d (%) is the percentage proportion of sediment discharge that is transported. Sediment loss is a function of the sediment discharge and the proportion of sediments that continues to be transported in the irrigation canals. The water and sediments that continue to be transported are then distributed among the network of irrigation canals that then discharge into the block of 90 fields.

Sediment Accumulation

Sediments discharged into the field then accumulate as a function of the sediment discharge and the bulk density of the sediments, constrained by a soil compaction factor (van Rijn 2013; Wilkinson *et al.* 2006, 7):

$$\Delta H_i = \frac{\Delta S_{tot,i}}{f_i}$$ Equation 10

where:

$$\Delta S_{\ tot,i} = \frac{Q_{s,i}}{BD} . \frac{1}{C}$$ Equation 11

ΔH_i represents the depositional layer thickness (m), $\Delta S_{tot,i}$ represents the total sediment volume in a given stone-bound field i (m^3 day^{-1}), f_i is the area of a given stone-bound field *i* (m^2), $Q_{s,i}$ is the sediment discharge within a given stone-bound field *i* (tonnes day^{-1}), *BD* is the bulk density of soils (1g cm^{-3} or 1000kg m^{-3}), and *C* is a consolidation/compaction rate of soils (days). The model makes the assumption that majority of the sediments fall within the bulk density of clays and bulk density rates are therefore constrained to the ranges for clays and silts in the model (see sections above).

4.2.4 ESTRaP Model Sensitivity Analysis

Global sensitivity analysis of the model was conducted using the NetLogo BehaviorSpace and R 3.3.3 to explore the various model parameters in a systematic way. This was in order to explore the model behaviour for varying parameters and how they affect model outputs in order to see which parameters had the greatest influence on model outputs. The outputs were then graphically visualised in R using ggplot (Wickham 2009) to assess the sensitivity of the model to variations in model inputs. The three main parameters of TSS, water depth in channels and Manning's roughness coefficient (n) have a great influence on the output variables under observation i.e. water and sediment discharge rates and the accumulation of sediments within the fields. Global sensitivity analysis was conducted where the selected input parameters for the model was run over all combinations of the main parameters and iterated for 365 time steps to represent a year.

Table 7: Model parameters used for global sensitivity analysis in BehaviorSpace

Parameter	**Min value**	**Max value**	**Varied by**
Water depth	0.05	1.0	0.05
TSS	50	800	50
Manning's n	0.01	0.1	0.01

Exploratory global sensitivity analysis of the data shows that water and sediment discharge varied with water depth while sediment discharge also varied with TSS (Figure 23 and Figure 24). As the water depth within the canalised streams and irrigation channels increased, the amount of sediment being discharged into the stone-bound fields increased even as the total suspended sediments were held constant (Figure 23). This ties to existing literature that estimates suspended sediment discharge through the linear interpolation of estimated suspended sediment concentration and water discharge (Gray and Simões 2008, 1066). The increase in sediment discharge can be related to the depth of the water column in the channels which allows for more water to flow through at a given time and thus transport more sediment. This means that even in instances where there is low sediment input from the surrounding catchment, possibly due to vegetation cover, variations in the water depth from increased water availability would influence the sediment discharge downstream. This can be linked back to section 4.2.1.2 on the model assumption that surface runoff and erosion is negligible across the landscape due to the series of stone-bound fields that would limit erosive processes. The water depth and water discharge also affect sediment discharge particularly of fine sediments as these fine particles can be transported at low water discharge rates (Steegen *et al.* 2000, 31). This means that even in instances where water depth is low, sediment discharge of fine sediments will still occur. Therefore where fine sediments such as clay particles make up the majority of the total suspended sediment concentration, low water depths and slower water discharge rates can effectively transport sediments and the TSS volume becomes the predominant factor influencing sediment discharge (Figure 23).

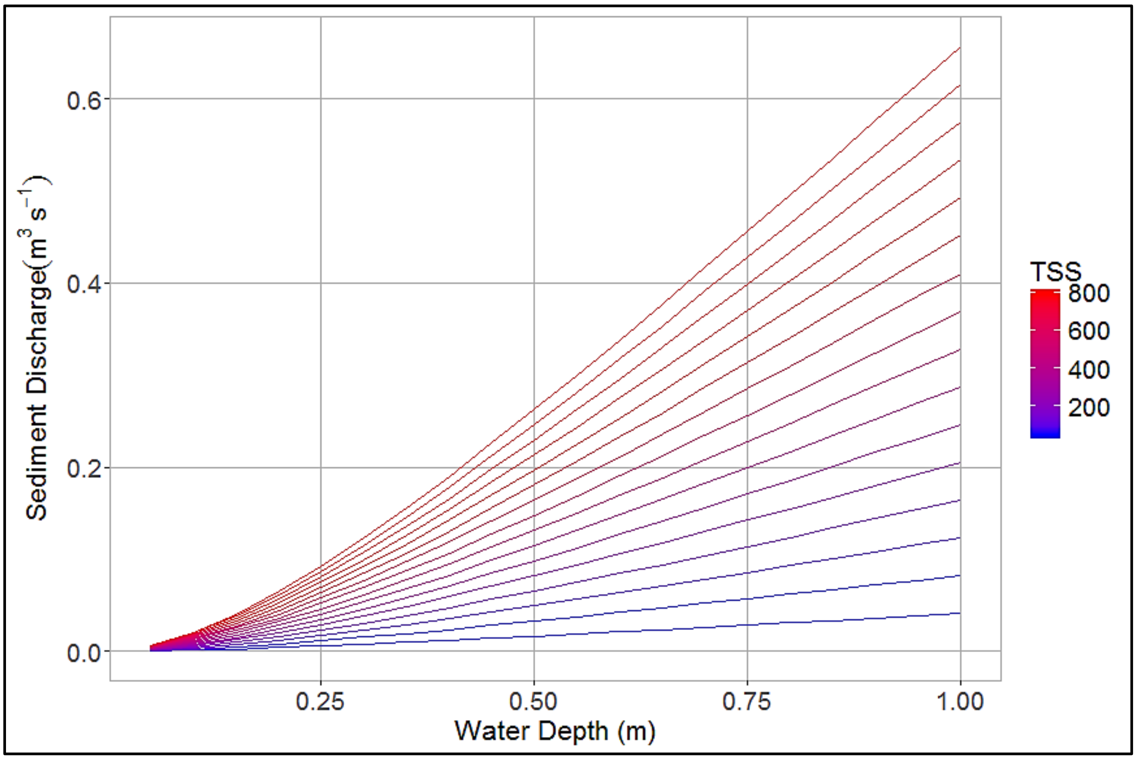

Figure 23: Variations in mean annual sediment discharge (m^3 s^{-1}) with increasing water depth and total suspended sediment (mg L^{-1}) with Manning's n of 0.03

The sediment discharge also increased with increased suspended sediment volumes (Figure 23). Thus at a constant water depth increased TSS would result in increased sediment discharge. This is relevant in representing increased incorporation of sediments into the water channels during rain storm events and understanding the changes in sediment discharge between different seasons. Studies by Nu-Fang (2011) found that suspended sediment yield varied with the different seasons and was highest when water availability was greatest. The variability in TSS would therefore also affect the amount of sediment discharged and accumulated within the field system. Since sediment discharge is a linear function of water and TSS, increase in the TSS values would therefore result in increase in the sediment discharged and therefore the accumulation rates in the fields. For the purposes of this model, a combination of variation in water depth and constant TSS would support representation of seasonal variations that would influence sediment accumulation as outlined below. Results of field studies conducted on water channels in the Engaruka found TSS values ranging from 50 to 800 mg/L as outlined in Chapter Two, with the average TSS of 200 mg L^{-1}. The model therefore uses initial TSS values of 200 mg L^{-1} and focuses on variability in water depth to simulate for the effects on water and sediment discharge.

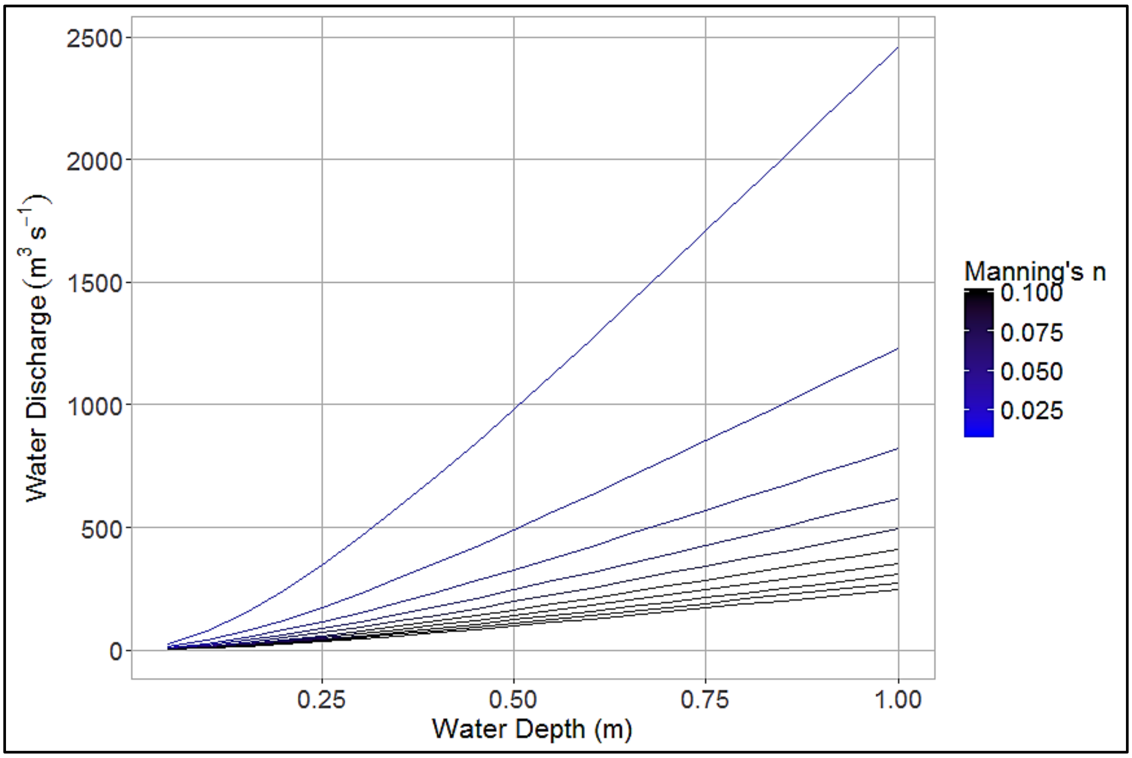

Figure 24: Change in mean annual water discharge (m^3 s^{-1}) with increasing water depth and changing Manning's roughness coefficient (n) values, with TSS of 200 mg L^{-1}

Water discharge was also found to vary with water depth and varying Manning's roughness coefficients (Figure 24). An increase in the Manning's n resulted in a decrease in the water discharge while an increase in water depth in the channels resulted in an increase in water discharge across all Manning's n values. Low Manning's n values are typical of the surfaces of artificial channels made with materials intended to reduce friction while natural channel surfaces tend to have higher roughness coefficients (Chow 1959). Based on data from Stump (2006a) on excavations conducted in Engaruka, the water channels modelled can be described as excavated or dredged, straight earth channels with earth bottoms and stone-lined channel sides. The calibration for these channels can therefore be adjusted to approximate n of 0.030 based on interpretation of Chow's (1959) reference Manning's n values.

Increase in water depth resulted in increased water discharge (Fig. 5) and while faster water discharge can seem useful in providing large supplies to fields, the high water flows within the channels can result in damage to the channel walls by eroding their surfaces. The preference would therefore be for lower water discharge at channel water depths of less than 0.50 m. Calibration for other aspects of the cross-sectional area of the channel i.e. bottom and top width and channel slope, were based on the archaeological data from excavations conducted by Stump (2006a). As discussed above, sediment discharge can be interpolated from water discharge and the model simulates the function as expected such that as water discharge increases sediment discharge also increases.

4.3 ESTRaP Model Scenario Implementation and Analysis

The model was implemented under a series of four scenarios to try to understand how the environmental factor of rainfall availability and variability, represented by water depth, would influence water and sediment discharge and eventually sediment accumulation. The implementation of these four scenarios would help define the timescales involved in accumulating sediments within the field system. By modelling these scenarios we would gain a better understanding of the long-term patterns of field development such as consecutive or concurrent field construction and ultimately supplement archaeological interpretations on the development and expansion of the Engarukan agricultural field system. Simulations were run for a period of 100 years to incorporate multi-decadal variability in climate conditions and the scenarios described utilised fluctuations in water depth within the channels to represent the variability in water availability. The model also assumes 100% sediment-trap efficiency, whereby all sediments discharged into the fields were captured and accumulated within those fields, total suspended sediments (TSS) were kept constant at 200 mg L^{-1}. The data values for TSS of c. 200 mg L^{-1} and the water depth of c. 0.1 m selected for the ESTRaP model were selected based on a hydrological study as discussed in Chapter Two.

4.3.1 SIM-O1 Constant water availability

In SIM-01 Constant water availability, idealised conditions of constant water availability over time were represented by a constant water depth of 0.1 m. This is potentially realistic particularly where perennially rivers can be found such as the

Engaruka River and the humans utilising the system can control how much water flows in the canals. The water depth selected was based on average water depth values from the results of a hydrological study for a 4 km section of the Engaruka River and adjacent offtake irrigation channels. This scenario is intended to demonstrate how always having constant water available would affect sediment accumulation rates.

4.3.2 SIM-02 Seasonal variability

In SIM-02 Seasonal variability, the climate in Engaruka follows a bimodal rainfall pattern during a calendar year (Figure 25) with two wet seasons interspersed with two dry seasons (Jones and Harris 2008; Ryner *et al.* 2008).. These fluctuations could have corresponding effects on the water and sediment discharge and the amount of sediment that accumulates within the fields.

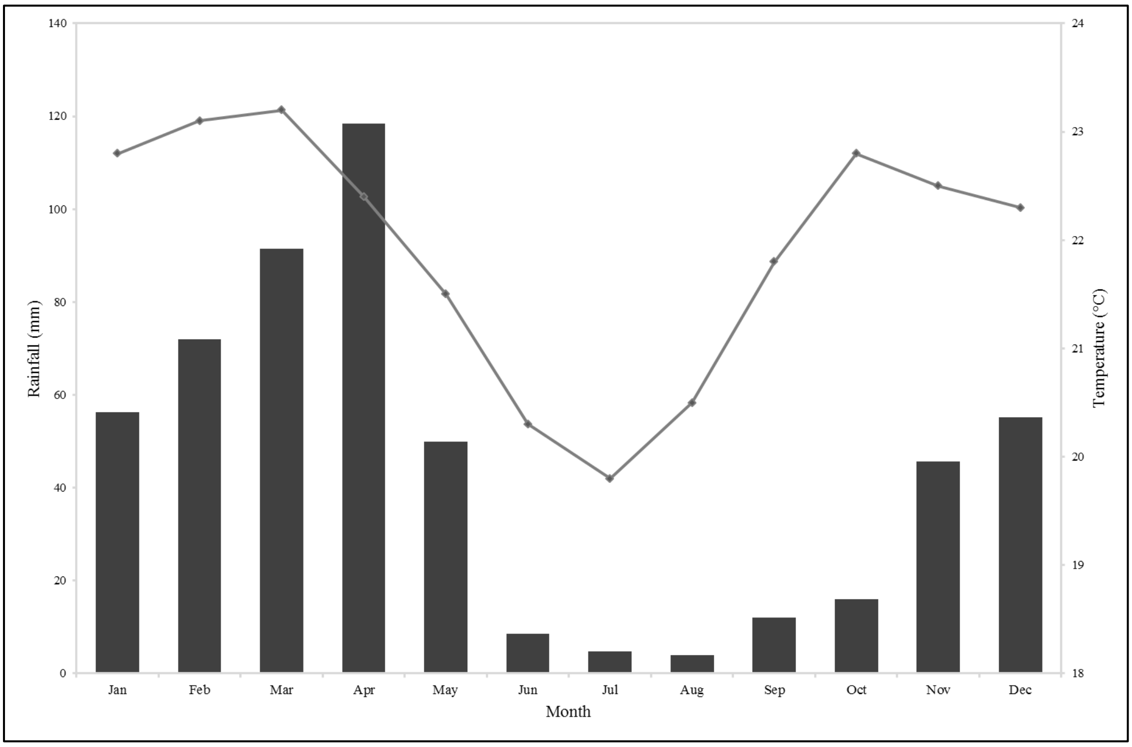

Figure 25: Average monthly rainfall (bar) and temperature (line) for Engaruka, Tanzania from CRU time series high resolution gridded datasets 1901-2009 (Jones and Harris 2008).

The conditions simulated in SIM-02 therefore vary water depth to simulate seasonal fluctuations in water availability in order to determine how these fluctuations affect sediment accumulation rates and sediment depths. The seasonal variability was designed in the model by varying the constant water depth of 0.1 m by 20% to represent seasonal fluctuations in water availability. The 20% was an arbitrary range based on observations of the highest and lowest values of water depth from the hydrological study discussed in Chapter Two to represent a simply range in the model. One of the main scenarios therefore simulates these seasonal fluctuations in order to understand the influence of this variability on sediment transport and accumulation within the fields.

4.3.3 SIM-03 Long-term Climate variability

In SIM-03 Long-term climate variability, the combination of seasonal variability with longer term climate variability that is also evident within the East African region is simulated. Studies conducted using some palaeoclimatic proxies (Marchant *et al.* 2018; Westerberg *et al.* 2010, 305; Ryner *et al.* 2008; Barker and Gasse 2003; Verschuren *et al.* 2000) show that over the last 1,100 years the East African region has experienced warmer, wetter climates interspersed with long periods of drought at a decadal scale. In addition, studies by Jones and Harris (2008) have shown evidence of these decadal fluctuations (Figure 26) which would also have influenced water availability. The climate time series presented here is illustrative of the cycles of wetting and drying periods that were experienced in the Engaruka system. Time series analyses were not conducted onto determine the pattern of cycles and the model employed alternating patterns of wetter periods, moderate conditions and drier periods in decadal blocks.

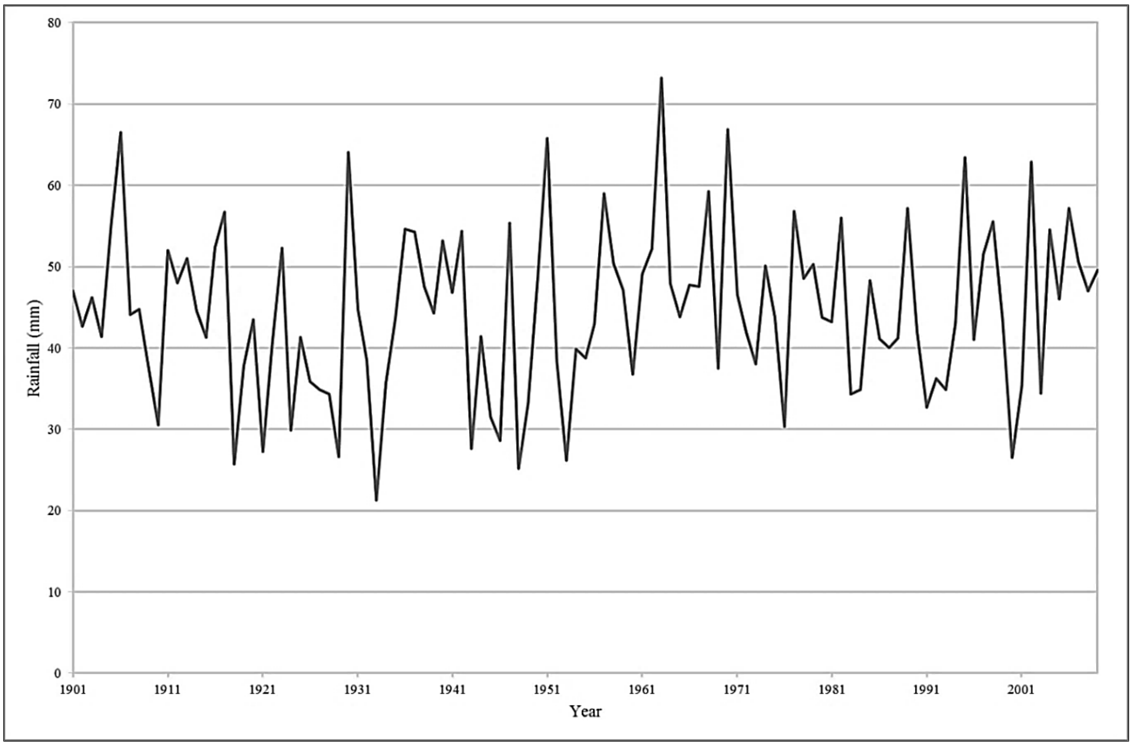

Figure 26: Annual rainfall for Engaruka, Tanzania from CRU time series high resolution gridded datasets 1901-2009 (Jones and Harris 2008).

To simulate some examples of long-term climate variability, multi-decadal droughts were incorporated based on palaeoclimatic proxies (Verschuren *et al.* 2000) that show evidence of long periods of drought that fall within the time period in which the Engaruka field system was in use. The conditions simulated in SIM-03 combine seasonal fluctuations in water depth with simulations of water depths that relate to more prolonged periods of drought or relatively wetter conditions. This simulation is intended to determine how prolonged variability in climatic events, similar to those that occurred during Engaruka's period of occupation, affects sediment accumulation

4.3.4 SIM-04 Impact of vegetation cover

In SIM-04 Impact of vegetation cover, in combination with seasonal variability, the vegetation cover of a landscape also influences water and sediment discharge rates with runoff increasing by approximately 30% on bare ground as compared to areas with vegetation cover (Lesschen *et al.* 2009). The model employs a generic representation of vegetation cover with the aim of focusing on how the absence of vegetation cover in the upland regions affects water flows within the rivers that would result in increased sediment discharge into the fields. This is due to the variability in representing surface runoff effects from different vegetation types both spatially and temporally (Lesschen *et al.* 2009, 177; Pilgrim *et al.* 1988, 388) with surface flows in grasslands showing discontinuity between bare ground and the vegetated patches. While the presence of different vegetation types such as grasslands can act to limit sediment runoff, the model makes the assumption that sediment runoff across the landscape is negligible (see section 4.2.1.2) and focuses on the sediment inputs already present within the channels that were transported from upland landscape sources. As has been discussed above, the Engaruka region experienced long periods of drought which would have had a significant effect on the vegetation cover upstream of the irrigation system. One of the possible outcomes of reduced vegetation cover would be increased surface runoff during rainfall events which could possibly result in increased water depth and elevated levels of entrained sediments in the channels. This increased water depth would then have an effect of water and sediment discharge rates into the fields. This would then have an effect on the volumes of sediments discharged into the fields and accumulated over time. SIM-04 therefore simulates conditions in which reduced vegetation cover, resulting in increased water depth from runoff, combined with seasonal variability in water availability would influence sediment accumulation rates.

The scenarios modelled are about end-members to constrain sediment-transport rates rather than being realistic representations of the compositional aspects of sediment-transport processes. This means that the scenarios focus on how variations in water availability influence sediment transport rather than representing all the dynamics of sediment transport processes.

4.4 ESTRaP Model Results and Discussion

4.4.1 Impact of water availability

The results of the model simulations provide information on the amount of time and rates at which sediments accumulate within a block of fields, averaged across the entire block of 90 fields. The four scenarios of constant water availability (SIM-01), seasonal variability (SIM-02), long-term climate variability (SIM- 03), and vegetation cover impact (SIM-04) were simulated for a period of 100 years with

SIM-01 showing the highest mean accumulation of sediments at 4.3 metres for the whole 3,000 m^2 block of 90 fields modelled (Figure 27). This was closely followed by SIM-04 at 3.9 m while SIM-03 had the lowest sediment depths at 2.3m and SIM-02 at 2.7 m.

The archaeological evidence from studies conducted by Stump (2006a) found that the fields within the North Fields section accumulated sediments to a depth of 700 mm across a 3,000 m^2 block of 90 fields. As shown below, the conditions modelled in SIM-01 and SIM-04 would have accumulated sediments to depths similar to those recorded archaeologically in 16 and 18 years respectively, while in SIM-02 and SIM-03 it would have taken 26 years to accumulate sediments to the depth of 700 mm across the 3,000 m^2 block of 90 fields (Figure 27). Given the time it would take to accumulate sediments across the fields, 16 – 26 years, it would take approximately 2 – 3 months to build each 6 x 6 m field individually.

The sediment depth of 700 mm across the block of 90 fields represents a maximal depth of accumulated deposits with the assumption that the fields are of equal dimensions. Given the slope of the land, it is more likely that the fields upslope of the canalised stream (as seen in Figure 22) would be shallower than those closest to the canalised stream, resulting in a wedge shape. This wedge shape would result in lower sediment depths in the upslope fields as compared to those adjacent to the canalised stream. The average sediment depth across the whole block of fields would therefore be approximately half of the maximal average depth of 700 mm to account for this wedge shape at c. 350 mm. The minimum time therefore taken to accumulate sediments would reduce, with sediments accumulating to a depth of 350 mm across the 3,000 m^2 block of 90 fields after 8 years for conditions modelled in SIM-01 and SIM-04, and 13 years for SIM-02 and SIM-03 (Figure 27). Given the time it would take to accumulate sediments across the fields, 8 – 13 years, it would take approximately 1 – 2 months to build each 6 x 6 m field individually. The simulations conducted within the ESTRaP model provide an indication of the maximum rates at which these sediments could have accumulated and allow for interpolations on how the fields were constructed. The short amount of time it would take to build each field means that farmers would have been able to construct fields over several cropping seasons, working over small sections at a time. This gives us a maximum and minimum temporal range for the development of the fields.

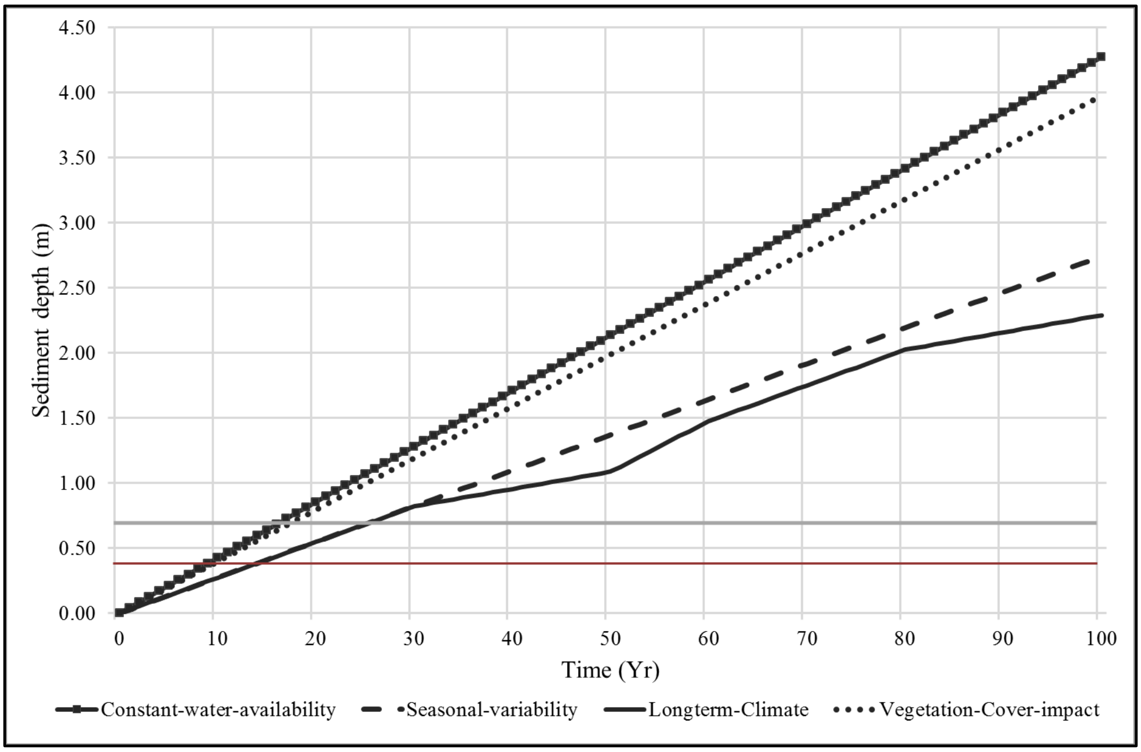

Figure 27: Mean annual cumulative sediment depth (metres) for a block of 90 six by six metre stone-bound fields based on simulations for four scenarios of constant water availability (SIM-01), seasonal variability (SIM-02), long-term climate variability (SIM- 03), and vegetation cover impact (SIM-04)over a period of one hundred years. The horizontal grey line highlights the sediment depth of 700 mm and the red line highlights sediment depths of 350 mm corresponding to those observed from the archaeological excavations

The high accumulation of sediments showed by SIM-01 was a result of the continuous supply of water at a constant water depth in the irrigation channels, with uniform amounts of sediments present, throughout the 100-year period. This constant, uninterrupted supply of sediments transported by the water would facilitate accumulation at a much faster rate as compared to the other scenarios (Figure 27, Figure 28). The scenario for constant water availability explored by SIM-01 ties to the ideal conditions of human-management of the field system through irrigation-agriculture, whereby in order to improve cropping conditions, the farmers in Engaruka developed the network of canals and stone-bound fields to provide a constant supply of water to their fields.

However, the idealised conditions presented by SIM-01 would not fully reflect real-world conditions of water availability in the sub-Saharan regions of eastern Africa. While the use of the irrigation channels and canalised streams would enable farmers to continuously direct water to the fields, maintaining constant water depths would be much more difficult due to seasonal and long-term changes in rainfall and water availability, and would result in variability in water and sediment discharge rates into the fields. Sediment accumulation would therefore be affected by the other scenarios of seasonal variability or long-term climate variability as shown by the sediment depths recorded by SIM-02 and SIM-03 respectively (Figure 27). As shown in Figure 27 and Figure 28, and discussed further in the sections below, the availability of water and variability in water depth in channels had an effect on the amounts of sediments discharged into the block of fields and the rate at which these sediments accumulated.

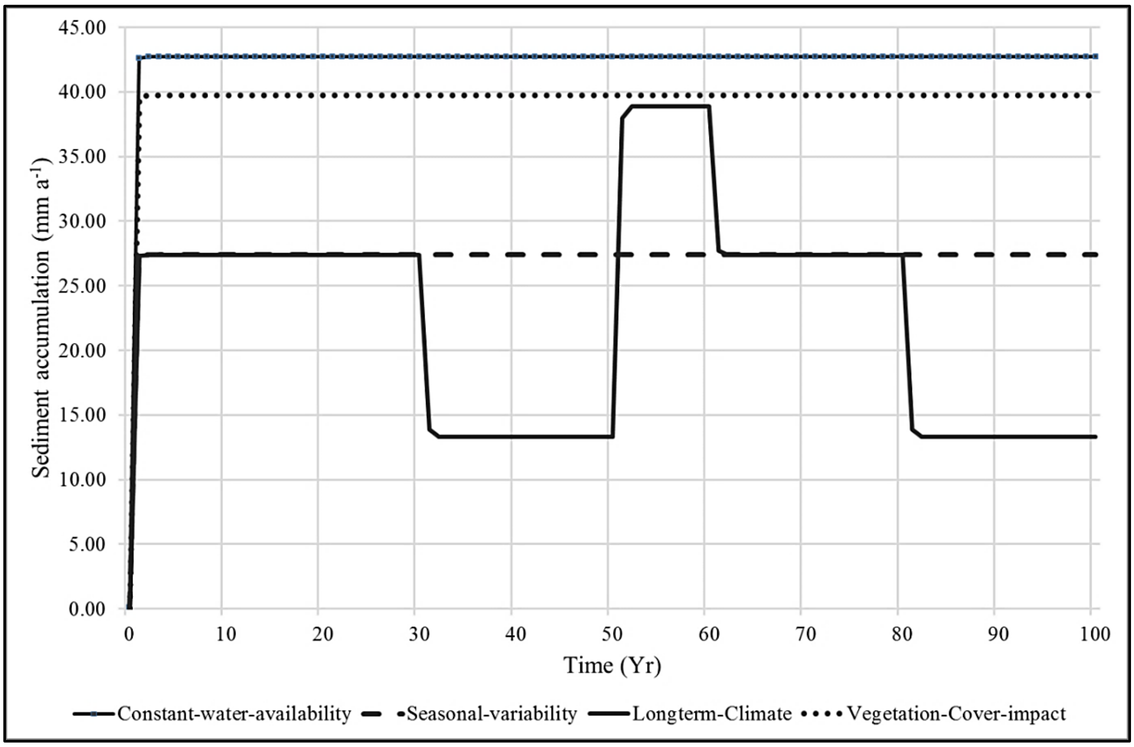

Figure 28: Mean annual sediment accumulation rates (mm a^{-1}) modelled for the four scenarios of constant water availability (SIM-01), seasonal variability (SIM-

02), long-term climate variability (SIM- 03), and vegetation cover impact (SIM-04) for a block of 90 fields over a period of 100 years.

Looking at the average annual rates of sediment accumulation for a block of 90 fields (Figure 28), SIM-01 had the highest rates at 42 mm a^{-1} per year followed by SIM-04 at 39 mm a^{-1} and SIM-02 at 27 mm a^{-1}. Longer term variations in climate account for the fluctuations in sediment accumulation rates seen in SIM-03, ranging from 38 mm a^{-1} during the much wetter periods to as low as 13 mm a^{-1} during the periods simulated for extreme dry conditions and an average of 22 mm a^{-1} over the 100 years. This lower mean annual sediment accumulation rate of 22 mm a^{-1} means that if would have taken 16 years for sediment depths to reach 350 mm across the 3,000 m^2 block of 90 fields. Sediments accumulated during the extreme dry conditions as the simulation was set to have a minimum water depth that would simulate low water availability but not complete absence of water. Given that the perennial Engaruka River was one of the water sources for the irrigation channels in the North Fields stump (Stump 2006a; Sutton 1998), water supply to the fields would have still been possible but the amount of water in the channels would most probably have been greatly reduced. There would have therefore been some sediment transport to the fields but at a much lower rate as indicated in SIM-03.

The annual accumulation rates were much higher for SIM-01 and SIM-04 as compared to those for SIM-02, while SIM-03 had the lowest mean accumulation rate of 22 mm a^{-1} over the 100-year period. SIM-02 and SIM-03 had periods in which sediment accumulation rates were similar such as between Years 0 -30 and Years 60 – 80 of 27 mm a^{-1}. This homogeneity in accumulation rates relates to similarities in the seasonal variability in water availability for the simulations. These similar conditions during these time periods relate to periods outside of extreme weather events such as droughts or when much wetter conditions occurred. Keeping in mind that these rates are annual averages of sediment accumulation, the influence of seasonal and long-term climate variability have a great effect on sediment accumulation rates over the 100-year period. The wetter and drier time periods in SIM-03 were represented by increasing and decreasing water depth values in the channels by 20% of those used to simulate conditions in SIM-01. The rise and drop in water depths resulted in respective increases and decreases in the volumes of water transported within the channels, with concomitant variations in water and sediment discharge into the fields. The increases and decreases in sediment discharge into the fields resulted in respective higher and lower sediment accumulation rates. The results of these simulations represent one way in which the availability of water influences the temporal scales for the build-up of sediments within the fields.

4.4.2 Influence of seasonal variability

The effect of seasonal variability within the model resulted in 2.7 m of sediment accumulating in the block of fields during the 100 years of the simulation (Figure 27) at a rate of 27 mm a^{-1} (Figure 28). The amount of time it would take to accumulate 350 mm of sediment within the fields was 8 years in SIM-01 for constant water availability but 9 years for SIM-04 and 13 years in SIM-02 and SIM-03 that incorporated seasonal variability (Figure 27). While the annual cumulative sediment depths presented reflect how sediments depths in the block of fields can increase over a 100-year period, these sediment accumulation rates tend to be constant when averaged out for each year but do not reflect seasonal fluctuations in water availability that would affect sediment discharge and accumulation within the fields (Figure 28). The influence of seasonal variability on sediment accumulation therefore was explored further to see how these intra-annual/daily fluctuations influence sediment accumulation rates (Figure 29 and Figure 30).

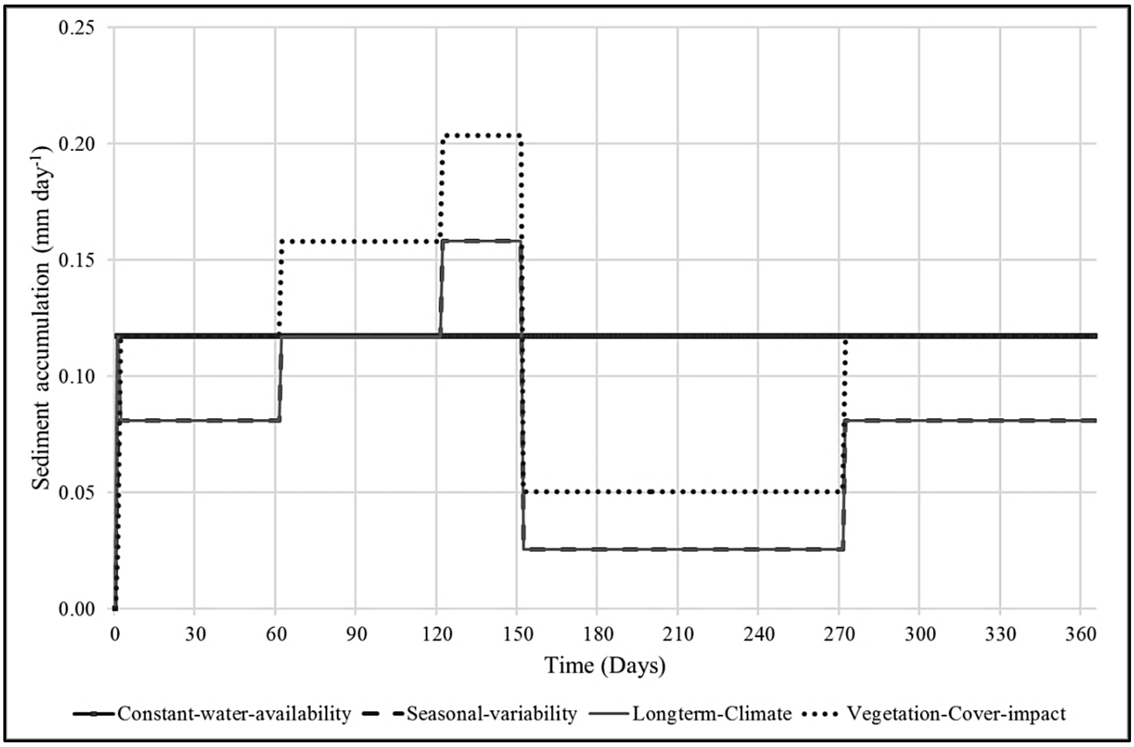

Figure 29: Intra-annual/daily sediment accumulation rates (mm day^{-1}) showing the variations in sediment accumulation over a one year period i.e. Year 1 of the model for scenarios of constant water availability (SIM-01), seasonal variability (SIM-02), long-term climate variability (SIM- 03), and vegetation cover impact (SIM-04).

Seasonal fluctuations in sediment accumulation simulated in the model showed that seasonal changes in water availability affected daily sediment accumulation rates (Figure 29). For SIM-02 and SIM-03, the average daily sediment accumulation rates ranged from 0.03 mm day^{-1} during the dry seasons to 0.08 - 0.12 mm day^{-1}, rising to 0.16 mm day^{-1} during the rainy seasons. While the daily rates for SIM-04 ranged from 0.05 mm day^{-1} in the dry season to 0.12 - 0.16 mm day^{-1}, and then rising to 0.20 mm day^{-1} in the rainy seasons. These rates contrast with SIM-01 where the daily rates throughout the year were constant at 0.12 mm day^{-1}. SIM-02 and SIM-03 exhibited similar fluctuations in sediment accumulation rates relating to seasonal variations in water availability. These lower rates would over time then result in lower annual rates and lower sediment depths as compared to SIM-01 and SIM-04 (Figure 28).

All the simulations except SIM-01 incorporated seasonal variations in water availability which then influenced sediment transport resulting in respective fluctuations in sediment accumulation in the fields. SIM-04 exhibited higher seasonal sediment accumulation rates as compared to SIM-02 and SIM-03, these higher rates of accumulation resulted in faster accumulation of sediments and would have taken less time to accumulate sediments than scenarios in SIM-02 and SIM-03. The scenarios show that less than 1 mm of sediment was accumulated across the block of 90 fields daily. The minute amounts of sediments accumulating point further towards the farmer's pattern of field development and show that the sequence of field construction outlined in Figure 22 above and by Stump (2006a) would have allowed farmers to build a block of fields quickly as they would not have been moving large amounts of sediments but would be instead working with small amounts deposited over time. The accumulation rates outlined in Figure 29 simulate moderate weather conditions, but during the periods of extreme weather simulated in SIM-03 (Figure 30), seasonal fluctuations dropped during the dry seasons and rose during wetter periods above those simulated for moderate weather conditions. Seasonal fluctuations continue to play a role in combination with these extreme weather events to influence the rate of sediment accumulation, as discussed below.

4.4.3 Impact of long term climate variability

Long-term climate variability combined with seasonality (SIM-03) had the greatest impact on the sediment accumulation within the fields, with scenarios showing that it would take 13 years to accumulate 350 mm of sediments across the block of 90 fields (Figure 27). As discussed above, SIM-02 and SIM-03 exhibited similar seasonal fluctuations in sediment accumulation rates in the first 30 years. However, over the longer timescales of the 100-year period (Figure 30) these seasonal fluctuations varied based on extremes of drought or wetter conditions. During the moderate weather conditions, sediment accumulation rates for SIM-03 ranged from 0.03 mm a^{-1} during the dry seasons to 0.08 - 0.12 mm day^{-1} and rising to 0.16 mm day^{-1} during the rainy seasons. When extreme dry conditions were simulated between Year 30 - 50 and Year 80 – 100, these sediment accumulation rates dropped to 0.01mm day^{-1} during the dry seasons to 0.03 - 0.08 mm day^{-1} and rising to 0.12 mm day^{-1} during the rainy seasons. In the wetter periods simulated between Year 50-60, these sediment accumulation rates rose to 0.04 mm day^{-1}

during the dry seasons to 0.12-0.16 mm day^{-1} and rising to 0.23 mm day^{-1} during the rainy seasons (Figure 30).

As shown in Figure 28 and Figure 30, the decreased sediment-accumulation rates in SIM-03 that simulate the long dry periods that Engaruka experienced, resulted in stark decreases in the daily sediment accumulation rates noted in Figure 30 between Year 30 - 50 and Year 80 - 100. As discussed by Ryner *et al.* (2008)and Verschuren *et al.* (2000), analyses of palaeoclimatic proxies show that the climate in the east African region alternated between dry and relatively wetter conditions as well as periods of prolonged dry episodes, with the Engaruka system in use during at least one of these prolonged dry periods in the 15th to 18th centuries CE. The model therefore simulated prolonged dry periods that Engaruka experienced as well as wetter conditions to illustrate the influence of these longer-term fluctuations on water availability and sediment transport and accumulation in the fields. During these drier periods between Year 30 to Year 50 of the simulation, the daily accumulation rates dropped to as low as 0.01 mm day^{-1}, with 0.12mm day^{-1} being the highest (Figure 30). These rates were much lower than the daily accumulation rates considered to be illustrative of moderate climate conditions, similar to those experienced today, seen in the first 29 years of the simulation (Figure 29). During this extensive dry period the water resources available were much lower than those of the moderate conditions, affecting water depths in the channels and thus the volumes of water and sediment discharged into the fields. In contrast, simulating wetter than average periods resulted in increases in sediment accumulation rates between Year 50 and Year 60 as water availability increased with increased rainfall. During these wetter periods, the daily accumulation rates rose, with the lowest rates at 0.04 mm day^{-1} and 0.23 mm day^{-1} (84 mm a^{-1}) being the highest (Figure 30).

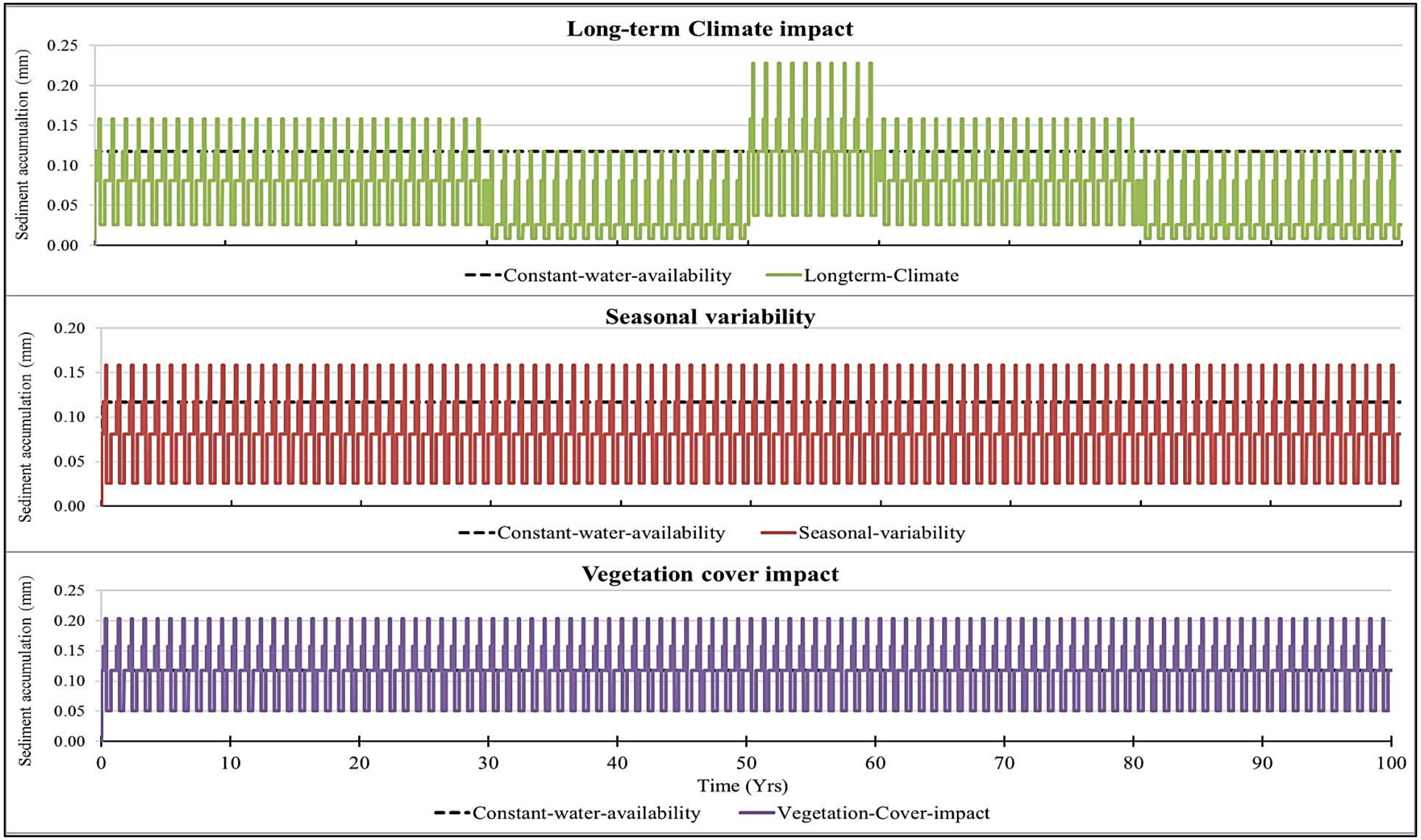

Figure 30: Daily sediment accumulation rates (mm day^{-1}) simulated for scenarios of constant water availability (SIM-01), seasonal variability (SIM-02), long-term climate variability (SIM- 03), and vegetation cover impact (SIM-04) over a period of 100 years.

These simulated extreme weather periods had long-term effects on the depth of sediments accumulated in the fields, with annual accumulation rates during moderate climate conditions averaging 27 mm a^{-1} while during the extreme dry periods between Year 30-50 and Year 80 - 100 these rates dropped as low as 13 mm a^{-1} and were highest during the extreme wet periods between Year 50 - 60 at 38 mm a^{-1} (Figure 28). These periods of extreme weather had a marked effect on sediment depth within the block of fields with the average depth at 2.30 m after the 100-year period, the lowest of all the simulations. This means that if farmers attempted to accumulate sufficient sediments to fill these fields, to the 350 mm depths observed archaeologically, during a comparatively wet period the fields could be filled in 9 years, but attempts to do the same during the conditions that prevailed during the dry period would take 27 years.

4.4.4 Impact of vegetation cover

SIM-04 on the impact of vegetation cover combined with seasonal variability resulted in high annual sediment accumulation rates at 39 mm a^{-1} (Figure 28). This scenario looked at how low or no vegetation cover could result in higher surface runoff and water influx into the channels which would then result in higher discharge rates and thus sediment accumulation rates within the fields. The block of fields took an average of 9 years to accumulate sediments to a depth of 350 mm across the c. 3,000 m^2 block of 90 fields. These high rates of sediment accumulation could also be seen in the daily rates for SIM-04, ranging from 0.05 mm day^{-1} in the dry season to 0.12 - 0.16 mm day^{-1} and then rising to 0.20 mm day^{-1} in the rainy seasons (Figure 29 and Figure 30). SIM-04 presents a case that takes into consideration the removal of vegetation cover within agricultural fields that could result in increased surface runoff for example if the fields are left fallow after a harvest and rains occur.

In addition, the possible removal of forest vegetation cover on the hillslopes upstream of the agricultural fields would have affected water availability in both dry and rainy seasons. Both these scenarios point to the possibility of higher influxes of water into channels and higher volumes transporting sediments, which could result in higher water and sediment discharge rates that could have allowed for faster accumulation of sediments within the fields. The faster accumulation rates as compared to SIM-02 and SIM-03 would have great impacts on how quickly sediments would accumulate and thus the timescales for the construction of the block of fields.

4.5 Water Availability, Sediment Accumulation and Field Development

The four scenarios influencing water availability explored in the model present important steps in understanding the temporal scales and patterns of field development that resulted in the expansion of the Engaruka water-management system. The scenarios discussed above point to the influence of water availability on the construction and development of a block of fields and the timescales involved. This variability relates to long-term climate changes that affected the east African region (Marchant *et al.* 2018). By focusing on specific aspects of water availability, we can use this information to understand the patterns of sediment accumulation and field construction that influenced the development of the Engaruka system. Understanding the impacts of seasonality, climate variability and vegetation cover on the availability of water and sediment accumulation helps support interpretations of the archaeological evidence by providing additional data to refine stratigraphic interpretations of the timelines and patterns involved in the development of the field systems. The results of this model support arguments put forth by Stump (2016) on the relevance of combining ABM with archaeological data for improved stratigraphic interpretations. The model focus on a block of 6 x 6 m fields in a small section of the Engaruka field system allows for quick analysis of sediment accumulation patterns. The results of these sediment accumulation patterns can then be extrapolated to assess the wider landscape particularly where there is no starvation of sediments as they have already been removed from the upslope areas.

The block of fields simulated in the model, utilising the wedge-shape illustration, took between 8 to 13 years, and up to 27 years during prolonged dry conditions, to accumulate sediments to a depth of 350 mm, given differing scenarios of water availability for sediment transport. This block of 90 fields covering approximately 3,000 m^2 forms one small part of the North Fields section that covers 9 km^2. The total volume of sediments required to accumulate sediment depths of 350 mm across the 3,000 m^2 block of 90 fields is c. 1,050 m^3, and to cover the entire 9 km^2 of the North Fields would require 3,150,000 m^3 of sediments. Annual sediment accumulation rates estimated from the ESTRaP model, and as discussed above, ranged from as low as 13 mm a^{-1} during prolonged dry periods in SIM-03 to as high as 42 mm a^{-1} in SIM-01. Annual sediment yields would therefore have ranged from 39 m^3 a^{-1} to 126 m^3 a^{-1} for the 3,000 m^2 block of 90 fields and if we extrapolate these estimates to cover the entire 9km^2 of the North Fields, 117,000 m^3 a^{-1} to 378,000 m^3 a^{-1} of sediments. These sediment yields rates are in order to build up the fields within the time period of 8 to 13 years.

The timescales for sediment accumulation relate to the block of 90 fields, at a finer resolution it would take individual 6 x 6 m fields between 1 - 2 months to accumulate sediments to 350 mm. This means that farmers can construct individual fields over a period of a single cropping/growing season. Comparing the model timescales and sediment accumulation rates to those estimated by taking into consideration the length of occupation of Engaruka point to much lower sediment accumulation rates. Given that the Engaruka system was occupied between the 15th and 18th centuries CE, if it took 300 years to accumulate the sediments to depths of 350 mm in the 3,000 m^2 block of fields, then the annual rates of sediment accumulation are estimated to be as low as 1.16 mm a^{-1}. However, this would assume that the field system was occupied and built at all times and that all sections are in use at all times.

While not explicitly modelled for the set of scenarios discussed, the role of the TSS plays an important part in sediment transport and accumulation. As shown in Figure 23, sediment discharge increased also increased with increased total suspended sediments. Thus at a constant water depth increased TSS would result in increased sediment discharge which would in turn result in increased sediment accumulation in the fields. For example, at water depths of 0.1 m, higher TSS entrained in flows would result in more sediments being discharged into the fields for the same water discharge rates. The sediments would accumulate at faster rates and this would affect the temporal scales for the development of the fields suggesting that the time taken to construct a 6 × 6 m field can be even shorter than the 1 to 3 months it takes in the modelled scenarios. Conversely, the water transported in the channels could contain lower TSS entrained in the flows resulting in lower sediment discharge rates and sediment accumulation taking longer than the modelled timescales of 1 - 3 months for a 6 × 6 m field. It is therefore important to take into consideration that the linear functional relationship between water discharge and suspended sediment is not always present in real-world estimations (Gray and Simões 2008). By varying the TSS and the water depth further expansions of this model can show the effect of varying suspended sediments concentrations on the temporal scales of sediment accumulation in the field system. In addition, seasonal storms in arid and semi-arid climates could result in the generation of high sediment runoff such as in Mediterranean systems. However despite these storm events, sediment runoff would be limited by the stony soils that dominate within these Mediterranean landscapes (Wainwright and Thornes 2004, 174). These stony soils exhibit low erodibility as compare to clay soils such as those modelled in the Engaruka landscape. However, the effect of seasonal storms would also be limited within the Engaruka field system as the series of stone-bound fields act to minimise the effect of erosive processes across the landscape.

The timescales presented by this model are at best ideal rates for how quickly the fields could be constructed, with further combinations of conditions resulting in longer or shorter sediment accumulation times. The model results nevertheless demonstrate that the fields could have been developed by utilising low flows of water in irrigation channels to transport and accumulate sediments in small field sections over successive seasons, supporting archaeological interpretations made by Lang and Stump (2017) and Stump (2006a). The sediment accumulation rates observed in the simulation demonstrate that field construction occurred over monthly and decadal timescales with small amounts of sediments being deposited at each given period of time. This would make field construction more manageable as farmers were not moving large sediment deposits but rather accumulating smaller amounts over time. In addition, because these sediments are not manually transported by the farmers, the accumulation of sediments does not generate high labour costs; resulting in more manageable labour expenditure for this system of intensive agriculture.

The amount of time it would take to accumulate sediments within each block of fields also points to concurrent construction of field blocks rather than consecutive construction. Given that it would take between 8 -13 years, and as long as 27 years during prolonged dry periods, to construct a block of fields covering 3,000 m^2 to sediment depths of 350 mm, if the fields are constructed sequentially, it could take between 24,000 – 39,000 and as high as 81,000 years to construct fields across the entire 9 km^2 that makes up the entire North Fields. These time scales are far beyond (and bordering on the impossible for) the indicated time periods in which Engaruka was believed to have been occupied. In addition, the North Fields section only forms part of the entire 20 km^2 field system with sediment depths in the South Field sections as high as 2.0 m (Lang and Stump 2017), proving that it would be impossible that the society in the Engarukan system relied on sequential field construction. Therefore, blocks of fields were most likely constructed concurrently across the North Field sections and sediments accumulated within them over successive seasons. In the model, water and sediment delivery was exclusive to the 3,000 m^2 block of 90 fields, if the North Fields was constructed in concurrent blocks of fields, this would affect the amount of water and sediment available to each block of fields, thereby increasing the timelines involved. The model can therefore be expanded in future to incorporate concurrent blocks of fields to determine how the addition of more fields can affect temporal scales in field construction.

Simulations for conditions shown in SIM-01 can be related to situations in which farmers would direct water exclusively to certain fields. Given the human-management aspect of this system, it is possible that farmers would have had further control over the movement of water and transport of sediments by closing off individual irrigation channels within the field system to direct water to specific fields. Evidence of this can be seen in the current farming practices employed in Engaruka (Caretta 2015) as well as in the traditional irrigation-farming system in Konso (Ferro-Vázquez *et al.* 2017; Watson 2009; Hallpike 2008; Amborn 1989) which continue to be in use in present day. The conditions in SIM-01 would allow farmers to quickly accumulate sediments and develop many concurrent blocks of fields across the system in a relatively short amount of time by concentrating the water and sediment resources in specific field blocks.

The ESTRaP model demonstrates the utility of agent-based modelling to assess the sediment transport dynamics and their influence on sediment accumulation and patterns of field construction. The model also addresses the issue of equifinality in the archaeological data, where it is argued that the construction of the field system either required large volumes of water in order to accumulate the sediments observed, or if the sediments could be accumulated using lower flows. For example, the farmers utilising low flows from water diverted from the rivers into irrigation channels would be able to transport and accumulate sediments in small field sections, or used much higher flows to flood larger areas and accumulate sediments quickly. This manipulation of the amounts of water flowing would influence not only the spatial scales but the temporal scales for the development of the field system as well as bringing to mind questions of consecutive or concurrent field construction where farmers would build fields only after previous field blocks had been constructed or build multiple field blocks concurrently where possible. This model demonstrates that the volumes of sediments observed in the field system could be accumulated to the sediment depths observed utilising low flows over a relatively short period of time. The combination of archaeological study with ABM techniques not only supports understanding of the hydrological processes of the system, but also points to other intangible factors not captured by the archaeology such as the patterns of field development employed by the farmers and provides temporal ranges for the construction of the field system. In this way agent-based modelling supports archaeological interpretations of the historical Engarukan water-management system and further advances our understanding of how this system was constructed and managed.

4.6 Conclusions

The three scenarios influencing water availability explored in the model present first steps in understanding the temporal scales and patterns of field development that resulted in the expansion of the Engaruka water management system. However, while these scenarios presented focused on water availability driving sediment accumulation, the current model assumes constant supply of sediments, future work into the model would attempt to explore this further by varying sediments to see the effects on sediment accumulation.

The ESTRaP model demonstrates the role of sediment transport on the patterns of field development that would have occurred and support archaeological interpretations of the sequence of field development and expansion by demonstrating that field blocks were developed concurrently across the field system rather than sequentially. The model results support archaeological interpretations where little additional information about the system is available, making this model particularly relevant to other sites and studies for which little data is available.

The model results show that the fields can be constructed over a short period of time, approximately 1-3 months per 6 x 6 m field and that it would take between 8 to 26 years, and up to 54 years during prolonged dry periods, to construct a block of 90 fields covering 3,000 m^2. In addition, sequential construction across the 9 km^2 of the North Fields would take between 24,000 – 81,000 years. Given the geoarchaeological evidence from OSL dating discussed in section 4.2 that highlight the timelines for the deposits in the fields as being between 700 ± 120 CE to 1860 ± 110 CE, the archaeological interpretations of the timelines for which Engaruks was occupied do not match with the timelines required to construct field blocks sequentially across the landscape. The results of the model simulations and the time scales for sediment accumulation point towards concurrent field development and expansion of the field system with farmers constructing blocks of fields concurrently across the North Fields rather than sequentially expanding across the landscape.

In the model, water and sediment delivery was exclusive to one block of fields, if the North Fields was constructed in concurrent blocks of fields, this would affect the amount of water and sediment available to each block of fields, thereby resulting in variations in the timelines involved for sediment accumulation. Future work into the ESTRaP model would explore construction of multiple blocks of fields to see the effect on the time scales for sediment accumulation. The expansion to multiple field blocks would also serve to discuss the dynamics of water and sediment allocation in relation to field placement. The current model focuses on variations in water availability driving sediment accumulation; however, other variables such as changes in total suspended sediments could also play a role.

Future work in the model could be expanded to look at variations in TSS in order to explore how variations in the amounts of sediments transported would influence sediment accumulation.

The ESTRaP model developed to simulate sediment transport and accumulation within the block of fields In the North Fields section of the Engaruka field system, produces estimates of sediment accumulation that support archaeological evidence of the duration of occupation and use of this system. The model presents an important resource in the assessment of sediment dynamics and patterns of field development that support archaeological interpretations not only for the Engaruka field system but can be adapted for other sites with evidence of sediment trapping. The use of irrigation canals as agents within the model allows for the expression of differences in canal structure that would affect the amount of water and sediment transported within the system. Further, the model compares the effects of variability of water availability that relate to climate change and the effects it would have on maintenance of such water-management systems. The results of these model scenarios would be of particular interest in understanding how other similar systems would have developed while taking into consideration the effects of long term climate on water availability.

Chapter 5 Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME-MACHINE) Model

5.1 Overview

The fifth chapter presents the Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME MACHINE) agent-based model which focuses on the landscape scale dynamics and human decision-making processes that led to the development of the Engarukan system, incorporating the environmental and human factors that would have influenced the development and continued use of the system. The problem that the model addresses is discussed and the purpose of the model is outlined. Model assumptions are discussed to outline what the model does and does not address. The parameters central to the development of these models are explained and data sources for these parameters outlined. The climate scenarios that influence soil moisture availability and social scenarios of alternative subsistence activities, social norms and population size that form the model simulations are outlined. The scenarios implemented in the models and the results of the analyses conducted are then discussed. The interpretations of model outcomes are discussed and related to existing literature, and the impacts of these interpretations on our understanding of the Engarukan water management system are summarised.

5.2 TIME-MACHINE Model Design and Development

The potential of water-management systems and techniques such as irrigation to improve agricultural productivity in sub-Saharan Africa have occupied both colonial and contemporary development debates (Schut *et al.* 2016; Stump 2010a; Adams 1991, 287). This is because the variability in water availability in the semi-arid and arid regions has great consequences on agricultural productivity (Rockström and Karlberg 2009; Oweis and Hachum 2006; Agnew and Anderson 1992; Critchley and Siegert 1991). Historic water-management systems in eastern Africa such as Engaruka in Tanzania present interesting questions for researchers as we currently do not understand how these water-management systems developed and thrived in these arid and semi-arid regions. In addition, recent development debates have focused on the sustainability of these systems with poorly performing contemporary systems contrasted with historic systems whose longevity has been interpreted as a sign of their sustainability (Woodhouse *et al.* 2017; Stump 2010a, 1253; Adams 1991; Adams and Anderson 1988). The archaeological evidence of the extensive scheme of agricultural fields and irrigation canals of the historic Engaruka water-management system point to sophisticated practices that might offer solutions to modern challenges of improving crop production to meet population demands (Stump 2010a; Adams and Anderson 1988) as well as insights into the environmental, human and capital resource interventions that were required for these systems to be sustainable.

As discussed in Chapter One, numerous archaeological studies conducted on the historical water-management systems in eastern Africa have found that the societies utilising these systems employed a wide variety of agricultural intensification practices. These water-management systems range from simpler systems of opportunistic floodwater cultivation and flood recession farming to complex systems that involved river diversions, water storage and canal and terrace construction (Stump 2010a; Tagseth 2008; Widgren and Sutton 2004; Adams and Anderson 1988). The differences in techniques employed point to the wide range of environmental and human factors that influence the development of these systems such as topographical and hydrological considerations and population dynamics such as the need to intensify agriculture to meet population demands, as well as adaptive strategies to deal with soil erosion or long periods of extreme weather such as extensive droughts. Some archaeological studies have provided insights into the impacts of some of these water-management systems on the surrounding environment and the socioeconomic dynamics of the communities that utilised them (Stump 2013; Stump 2010a; Widgren 2010; Harrower 2008; Costanza *et al.* 2007). Studies conducted in Konso have combined archaeology with geochemical and micromorphological studies to understand the effect of the water-management infrastructure such as terraces on land management and landscape modification (Ferro-Vázquez *et al.* 2017). Other studies that have combined archaeological data with socioenvironmental information such as on the Hohokam, USA, have involved mapping out the archaeological evidence of the irrigation system and assessing the hydrodynamics of the hydraulic structures (Purdue and Berger 2015). However such studies tend to focus on the influence of either environmental or human factors, but the wide range of interacting factors that lead to the development of such a system, such as the historical Engaruka water-management system, mean that understanding of the development and sustainability of such systems is limited.

Studies to explore the organisation and development of historical water-management systems have utilised agent-based modelling to try to understand how these systems functioned. Early models such as the Artificial Anasazi model (Axtell *et al.* 2002) looked at the population dynamics of an agricultural society and while not specifically related to water-management, this model provided a template for the use of ABMs in combination with archaeology to try and understand the evidence found in the archaeological record. ABMs that look at water-management in irrigation systems such as the model for the Bali temple system (Lansing and Kremer 1993) showed the role of social organisation in management strategies and how coordination amongst agents can arise from local interactions. The focus of the Balinese temple model was on the role of self-governance and the impact the different levels of social organisation and coordination had on the environment, in this case, the effect of synchronisation of water use on crop yields (Janssen 2007). While the Bali system focused on coordination amongst the agents this may not necessarily be true of other systems where rather than collective decision-making there would be other factors that affect individuals' actions. Other more recent ABMs such as the MayaSim model (Heckbert *et al.* 2016) of the Maya socioecological system have looked at the resilience of the system in terms of population demographics and environmental factors. However, the model does not explore the complexity of water-management that would have been involved in the development of the agro-ecological system. This is a crucial aspect that needs to be understood of the Engaruka system as the decision-making involved does not only influence the management of the system but also how the system came into being, and is a factor for its continued use. These decisions can be dynamic and range from individual to collective decision-making. Other ABMs such as those looking at the Hohokam system incorporate human decision-making on the management of an irrigation system with environmental changes over time and the management of the canal system and the hydraulic dynamics (Ertsen *et al.* 2014). While this model presents a finer scale in the interplay of the irrigation structures with human decision-making in the face of environmental factors. The factors that led to its development and the emergence of the agent decision-making are not explored.

Archaeological and geoarchaeological studies conducted by Lang and Stump (2017) on the Engaruka landscape provide information on the scale and complexity of the Engaruka system's infrastructure as well as pointing towards the patterns of construction and resilience over time. However, while the archaeological evidence from these water-management systems can provide information on the spatial extent and structural complexity of the systems that were developed and utilised, in many cases these systems have long been abandoned and little information is available on the environmental, socioeconomic and political factors that influenced their development and continued use. In addition, not only would different environmental and human factors affect the development of these water-management systems but the influence of these factors and their interactions change over time and geographically, affecting the system's development, continued use and sustainability.

The Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME-MACHINE) agent-based model uses a simulated version of part of the Engaruka landscape with Agent-Based modelling (ABM) techniques in the NetLogo platform to address these issues, employing data from modern human decision-making for irrigation management at Engaruka and palaeoclimatic data from the region (Ryner *et al.* 2008; Verschuren *et al.* 2000) to simulate different climatic scenarios that affect water availability. The ABM developed can be used to simulate scenarios of human-environment interactions for historical systems in combination with the archaeological data to support the simulation reconstructions (Cegielski and Rogers 2016, 287). The TIME-MACHINE model integrates both environmental and human factors that influenced the development of the historical Engaruka water-management system as well as the interactions of these factors to understand how they influenced the development and sustainability of the system over time. The model differs from other models discussed here as it incorporates both small scale household decision-making on the management of the irrigation system with longer term environmental changes to assess the interactions of these environmental and human factors across a temporal scale. The TIME-MACHINE model allows household decision-making as well as for the individual households to be influenced by the choices of their neighbours. In addition, the model utilises interpretations derived from palaeoenvironmental proxies for the reconstruction of climatic conditions in order to understand how climate change influenced the sustainability and continued use of the system. The techniques employed have the potential to contribute to studies on the sustainability of historical water-management systems and can advise strategies for modern systems by providing information on the development and management of the system over centuries rather than simply over the few years available to modern observational studies (Barton *et al.* 2015, 598). In addition, understanding the responsiveness of the communities and adaptations employed in response to changing environmental and human factors would contribute to modern development agendas for the running of contemporary water-management systems.

5.2.1 TIME-MACHINE Overview/Problem

As discussed in Chapter One and Four, the historical Engaruka irrigation-agriculture water-management system stands out as an example of the utilisation of water and sediment transport and landscape modification. The TIME-MACHINE ABM developed here aims:

- To assess the extent to which the modification of water movement and sediment deposition through irrigation influence crop productivity and crop yields within a section of the Engaruka field system.
- To understand the overall effect of environmental and human decision-making factors on the development and continued use of a section of the Engaruka field system.

The historical Engaruka water-management system believed to have been in operation during the 15th to 18th centuries CE (Lang and Stump 2017), presents interesting questions on the interaction of factors that influenced its development. This extensive system of irrigation canals, stone-bound, sediment traps and terraces has been categorised by researchers into three distinct sections of the North, Central and South Fields (Figure 31) (Lang and Stump 2017; Stump 2006a).

Together these represent a complex water-management system that has been the subject of development debates (Stump 2010a). The use of irrigation-agriculture water-management systems can be seen as an adaptation in response to changes in environmental or socioeconomic conditions, which could result in a more sustainable and resilient system in some instances. In the Engaruka system, exploring some of these factors and their interactions can help us understand how the community was able to adapt over time. On the one hand we have the environmental factors of water availability and long term climate change that affect soil moisture and in turn crop yields. In semi-arid ecosystems, the amount of rainfall and availability of water resources represent the limiting resource in agricultural production (Oweis and Hachum 2006; Critchley and Siegert). Water availability and the geographic distribution of water resources play an important role in the development of historical societies and in particular agricultural communities. The availability of water can place constraints on agricultural production and the development of human settlements. While it is possible to establish human settlements and the requisite food production in areas with limited water resources, this would require significant investment in the labour and infrastructure necessary for water manipulation (Scarborough 1991, 103).

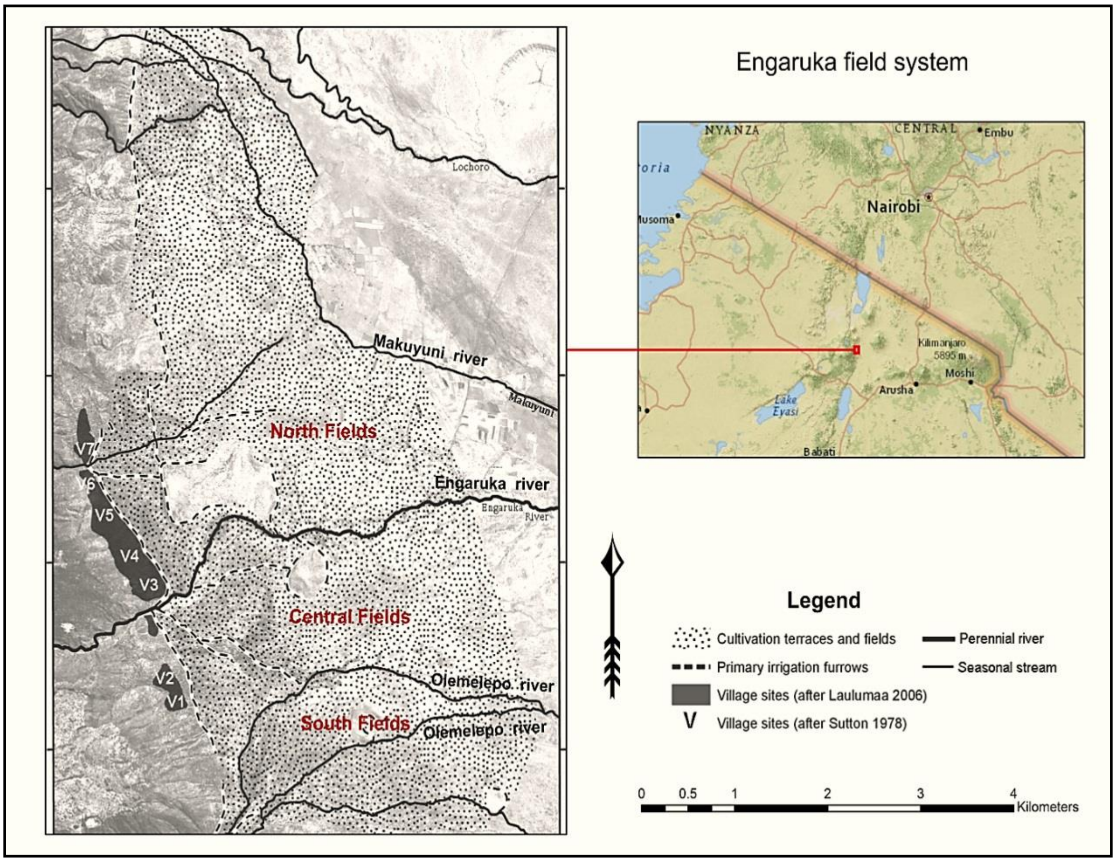

Figure 31: Location of the Engarukan water-management system and extent of the agricultural field system with river sources and village settlements Source: National Geographic World Map (Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC)

On the other hand we have socioeconomic factors that influence decision-making, such as alternative socioeconomic activities that provide equal or greater returns as compared to agriculture, which can result in farmers leaving agriculture for other subsistence activities. In addition, decision-making can be influenced by social norms that might encourage farmers to stay in agriculture, despite poor returns. By modelling the influence of the addition of irrigation water on soil moisture we can then assess the role this has on crop yields and the decisions of farmers to continue using the system. By modelling socioeconomic decisions by farmers to choose other alternative subsistence activities or the influence of surrounding neighbours on their choice to continue with agriculture, it is then possible to assess the influence these choices had on the continued use and expansion of the field system. By assessing the interaction of factors on the development of the modelled Engaruka system, we can then assess the influence of these factors over time. In doing so, we can thus understand the factors that influenced the development of the system and its sustainability temporally and spatially.

5.2.1.1 Purpose

The purpose of this model is to determine the influence of environmental and human factors i.e. climate change, water availability, social norms and other subsistence activities on the resilience of the historical Engarukan irrigation agriculture system.

The model aims to determine the extent to which various environmental and human factors influenced the development of the Engarukan irrigation system and the implications of these responses on the resilience of the system. In particular, what environmental and social factors influenced the development of agricultural production and the continued use of the system over time and to what extent? How did the interaction of the socio-environmental factors influence the continued use of the system over time?

The model is designed for researchers (particularly those interested in interpreting agricultural systems from archaeological evidence); exploring the resilience of historical and contemporary irrigation systems based on a variety of scenarios; as well as for development agencies interested in assessing the sustainability and resilience of various irrigation development practices using historical data and various socioeconomic and environmental scenarios. By looking at an integrated framework of interacting environmental and social factors, the model will therefore be able to highlight the factors that influence the resilience of the Engarukan irrigation system. The model description is based on the agent-based model description protocol and the updated ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006).

5.2.1.2 Model Assumptions

The model makes several assumptions for the hydrology and erosion dynamics, vegetation characteristics and farmer decision-making.

The hydrological dynamics of the landscape are influenced by the precipitation, which influences soil moisture changes through the interaction of infiltration and evapotranspiration; while the generation of runoff is a function of rainfall (Nill *et al.* 1996). The variability of available rainfall from season to season and across the landscape affects soil moisture dynamics with slope and vegetation type influencing the infiltration and runoff generation. In bare soils, less water infiltrates and more runoff is generated as compared to grass or tree patches (Rietkerk *et al.* 2002; Nill *et al.* 1996). The hydrological dynamics in turn influence the erosive processes with runoff generated influencing the amount of soil eroded (Wainwright 2006; Zhang *et al.* 2002). Vegetation cover in turn plays a role in the amount of soil eroded with bare soils having higher erosion rates as compared to patches with grass or tree cover.

The vegetation in the model is classed as savannah vegetation, with grasses dominating across the lower elevations at the foot of the hill slopes of the escarpment, while trees dominate on the hill slopes and higher elevations (Ryner *et al.* 2008). Vegetation distribution in tropical regions is influenced by rainfall and topographical factors of slope and elevation with higher rainfall i.e. > 650mm a^{-1} correlating with higher elevations, resulting in a dominance of tree cover; while lower rainfall at lower elevations results in tropical Savannah vegetation dominated by grasses (Bertram and Dewar 2013; Hession and Moore 2011, 1441; Staver *et al.* 2011, 1070). The changes in vegetation biomass and cover are in turn influenced by the soil moisture which affects the distribution of trees and grasses (Rietkerk *et al.* 2002). The model therefore primarily focuses on the influence of rainfall and precipitation on the hydrological, erosion and vegetation dynamics, as well as on human decision-making in agricultural practices.

Farmer decision-making in the model is centred at the household level to allow for both individual and wider social influences in decision-making to be expressed. The use of the household as the primary agent is due to the availability of data and the intention to focus on long term dynamics, which would be more easily observed at the household-level. In addition, the household is the most common identifiable agent in archaeological and anthropological studies such as on the Anasazi (Axtell *et al.* 2002), and households represent an identifiable unit within literature on historical societies. The availability of data, particularly social data on human decisions makes it difficult to assign a variety of decisions to individuals; this is especially the case of ethnographic data on agriculture and on historical societies. However, assigning decisions at the macro-level such as at the community-level as the most basic unit of agency, of which more generalised decision-making can be assigned, would mask the effect of individual decision-making while also obscuring the effect of the collective individual interactions on the society (Gómez-Limón *et al.* 2007). Therefore, the model is designed to allow decision-making at the household level, with different agents able to respond heterogeneously to socio-environmental factors while allowing for the emergence of collective interactions over long-term temporal scales. The model also does not make an assumption of ideological influences on agricultural activity and instead focuses on the decisions involved in agricultural activity such as meeting their subsistence needs (as outlined in the paragraph below). This is due to not only the limits of the available ethnographic data for this region, but also the extensive and varied cultural practices employed in analogous communities in the East African region (Stump 2006b, 145). This makes it difficult to objectively select cultural or ideological factors that would have affected farmer decision-making and thus in the model the influences on agricultural activity are primarily from environmental factors.

In addition, the farmer decision-making in the model is driven predominantly by the need to meet the subsistence and energy requirements of the household. The farmer decision-making is also guided by the fact that most subsistence agriculture in sub-Saharan Africa is rain-fed (Biazin *et al.* 2012). While this might be the primary target of the farming households a variety of criteria come into play to achieve this goal, both for rain-fed and irrigated agriculture (van Duinen *et al.* 2016; Weintraub *et al.* 2007, 97). Although many criteria and decisions are similar between rain-fed and irrigated agriculture, irrigated agriculture involves additional decision-making relating to labour inputs and competing water demands for human consumption, and the additional factor that risk versus potential benefits of greater yields need to be taken into consideration (Gómez-Limón *et al.* 2007, 94). The household agents in the model therefore incorporate a variety of criteria and decisions to meet a variety of subsistence needs. The model focuses on agent decisions of whether or not to engage in rain-fed or irrigated agriculture, the choice of alternative subsistence activities, and on the social norms where the choice of farming made by neighbours influences the agent's own choice of whether or not to continue farming.

5.2.1.3 Entities, State variables and scales

The TIME-MACHINE model is implemented in NetLogo platform version 5.2.1 (Wilensky 1999) and the model description is based on the ABM description protocol and the updated ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006). It consists of a simulated landscape representing the South Fields at Engaruka covering approximately 4 km^2 (Figure 31). To build the model environment, a georeferenced digital elevation model, the ASTER GDEM V2 (NASA_LP_DAAC 2011) was input at a 30 m resolution to provide the landscape for simulations. The agents within this landscape comprise of the farmer households.

In this implementation of the model, the South Fields section of the Engaruka field system incorporating farmer households as agents was modelled to understand the development of the field system, given simulated scenarios of different environmental and human factors. The model focuses on the influence of water availability and human decision-making and their interactions to determine if and how these factors influence had the greatest influence on the rise and continued use of irrigation-agriculture over time.

Farmer Households entities and variables

Farmer households are characterised by their energy or labour, the total number of fields they build, cultivate and irrigate, the number of canals they build, and memory of previous yields from cultivating fields. Farmers are also characterised by Boolean variables on decisions on whether or not to farm, build irrigation systems, expand or contract fields used, build canals and water fields, and whether or not to pursue other subsistence activities that are more viable or move to another region if agricultural production is not viable.

Engaruka South Fields Habitat entities and variables

The Engaruka South Fields habitat is characterised by state variables of rainfall, temperature, topography and slope. The habitat is represented by field patches with a spatial resolution of 30 m by 30 m, characterised by soil depth, elevation, flow, evaporation, sediment erosion and deposition, soil moisture, vegetation biomass and vegetation type. The climate follows a bimodal rainfall pattern and initial conditions are modelled from the interaction of precipitation and temperature based on global datasets (Harris *et al.* 2014) as discussed below.

Soil moisture and water movement are modelled as the units of water that infiltrate a given patch and the amount of runoff generated and transported downhill respectively; while net erosion is modelled as the function of the amount of soil transported and deposited for a given patch. The water entity is characterised by unidirectional flow. Erosion is modelled as the depth of soil that is removed by the action of flows across a given patch, while deposition is modelled by the loss of the forward momentum of the water flows that are transporting the sediments, resulting in sediments being deposited in a given patch based on the distance travelled. Vegetation type and biomass are modelled based on location and water variability, with patches containing fields designated with crop vegetation types, and surrounding vegetation modelled on savannah dynamics of tree-grass distribution.

Temporal and spatial scales

The model runs with a monthly time step; 12 steps making one calendar year. Data collected at each time step includes the soil moisture, net erosion, vegetation biomass and the number of farmer households and number of individuals in each household. The model is spatially explicit, and covers approximately 4 km^2 of the South Fields based on a georeferenced DEM. The DEM used to model the landscape i.e. USGS EarthExplorer ASTER GDEM V2 released in 2011 with a resolution of 30 metres (1 arc-second) (NASA_LP_DAAC 2011). The main model parameters, variables and default values are described in Table 8 and the sections 5.2.3 below.

5.2.1.4 Process Overview and Scheduling

Within the model, a series of processes take place each year, with agents also being responsive within the year at a monthly timescale as outlined below (Figure 32):

1. Rainfall is generated influencing soil moisture characteristics through the function of infiltration and evapotranspiration. Rainfall that does not infiltrate or evaporate contributes to the generation of runoff which flows downstream. The runoff affects soil depth and fertility through erosive processes. The amount of water that infiltrates, the runoff generated, and the rate of erosion are all influenced by the vegetation cover of the patches, with the soil moisture in turn influencing the changes in vegetation biomass over time.
2. At the start of the year, the farmer households decide whether or not to farm during the long rains season (month two to six), and the number of fields to be farmed, basing these decisions on the energy needs of the farmer households and number of individuals. If the farmer households have not planted crops during the long rains, then they do so in the short rains season (month nine to 11).
3. During the planting seasons, farmer households select farm patches based on suitability, such as proximity to the water channels and on areas with low slope angles. Initially farmer households rely on available rainfall to grow crops, but when soil moisture levels fall below a threshold, crops experience water stress and farmers decide whether to use canals to irrigate crops or plant more fields based on the rainfall available and their energy.
4. If the water available is not sufficient to grow crops, or the farms are far from a water source, the farmer households decide whether or not to water fields using irrigation canals. The farmer households establish canal systems to transport water from areas of high flows to their farms. The decision to use irrigation canals or plant more fields is based on whether they have the proximity to water channels. If they are not near a water channel then they plant additional fields. If they are closer to a water source then they set up irrigation.

5. Farmers allocate labour for agricultural activities based on their energy resources and the cost-benefit that arises. These tasks include clearing fields, weeding and watering during the cropping period and harvesting. This also includes the additional energy requirements of irrigation such as constructing and maintaining canals. The farmers must assess the cost-benefits of labour allocation to improve productivity. While they might require increased labour to improve fertility, such as in planting more fields or building irrigation canals, they may lack the energy resources necessary to do so. This affects their yields and has consequences on the decisions they make for the following planting season such as selecting to plant more fields in the following seasons or to build irrigation canals.
6. Farmer households harvest after the first rainy season (months seven to nine) and at the end of the year (month 12), and calculate their yield and energy cost, and note the number of fields used. If the fields have not been harvested by the end of the year, the farmers harvest them before beginning a new planting season. The individual farmer households maintain local knowledge of the number of fields they have planted and the yields obtained after each harvest. The farmers compare their yields to the ideal yields they would have received from alternative activities and make the decision to switch to the alternatives or continue with farming.
7. When making decisions to farm and the decision to prioritise farming over other subsistence activities, households are also influenced by social norms by the presence of other households also engaging in agriculture.

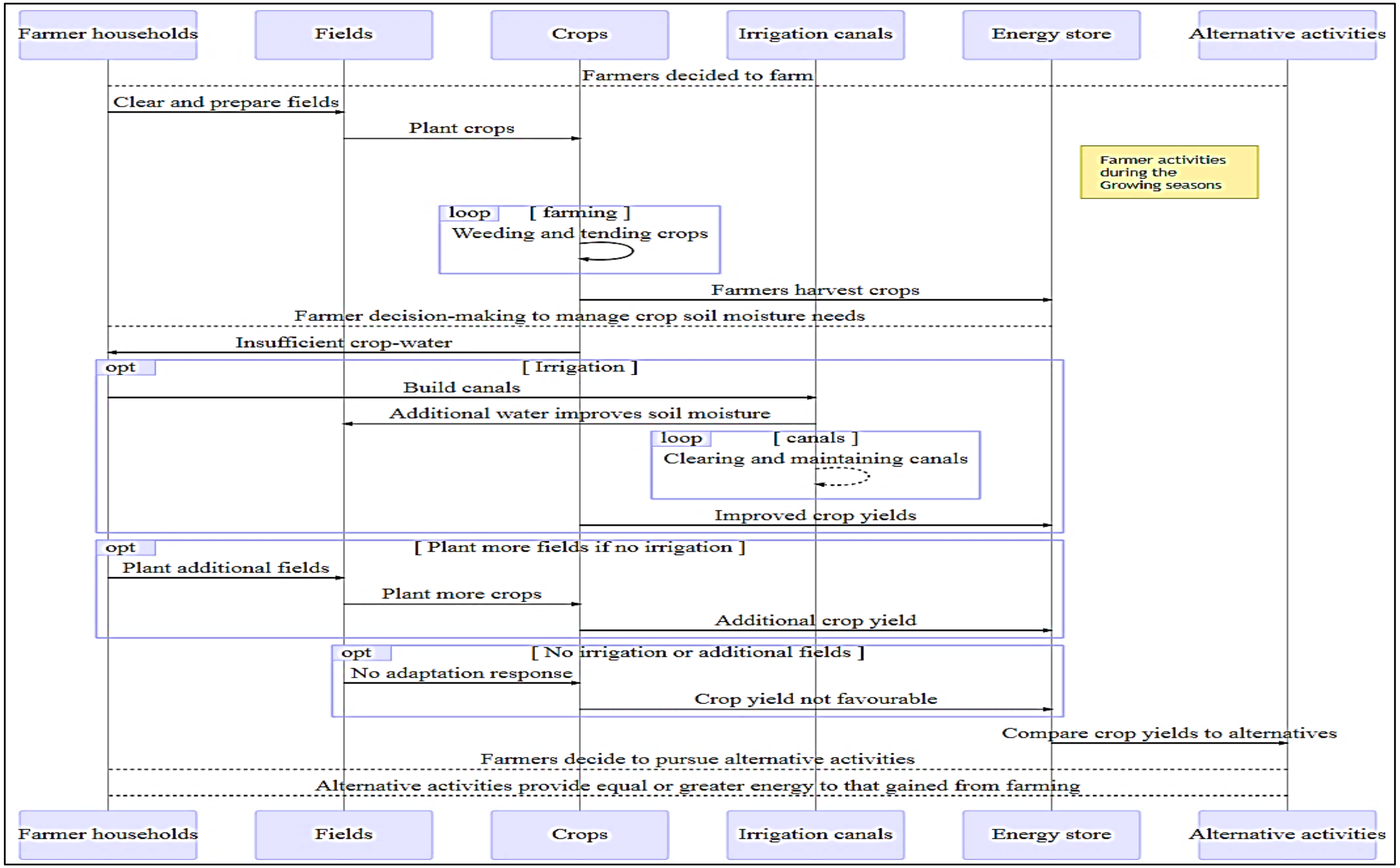

Figure 32: UML sequence diagram outlining the decision-making process of the farmer households from season to season

5.2.2 TIME-MACHINE Design concepts

The general concepts that underlie the model framework are presented below based on the ODD+D protocol (Müller *et al.* 2013; Grimm *et al.* 2006).

5.2.2.1 Theoretical and Empirical background

The model was designed to assess existing archaeological theories on the primary factors that influenced the development expansion and abandonment of the Engaruka irrigation system, and was informed by resilience theories (Marston 2015). The surface runoff, soil moisture and erosion and deposition are modelled based on standard hydrological approaches. The vegetation cover change and crop yields and crop water stress are modelled base on savannah dynamics and Walter's hypothesis (Bertram and Dewar 2013; Van Langevelde *et al.* 2003) as well as standard agricultural approaches of rain-fed and irrigated agriculture (Mutambara *et al.* 2016, 64; Biazin *et al.* 2012).

The agents' decision model is based on a combination of space theory-based models, i.e. their ability to select a suitable place to build fields and canals, and on experience/preference-based decision models (here derived from ethnographic histories and summaries of real world studies from analogous communities). The decision model is based on bounded rationality (Arthur 1994; Simon 1972) with agents only receiving partial information on water availability. Agents' behaviour is guided by heuristics (An 2012) and they engage in trial and error to determine their best irrigation and field expansion strategy based on their past strategies. In addition, farmer decision-making in the water-management system are influenced by both the effect of the environment, their response to these environmental factors, and the feedbacks from their alterations of the landscape to support irrigated agriculture (Özerol and Bressers 2017).

The decision model was chosen due to data unavailability for the community of interest; since the Engaruka households are no longer in existence, data was based on summarised data from analogous communities and on data from interviews and focus groups from Engaruka and Konso (see Chapter Two). The data was aggregated at household level.

5.2.2.2 Individual decision-making

Decision-making is localised at the household level. The farmer households decide where to build fields constrained with the decision to have the first fields along the river. Farmers also make decisions to expand or contract the number of fields used based on the available water and their decision to utilise irrigation canals; as well as whether or not to raise the field walls or to divert water to other fields when sediment levels are nearly equal to the wall heights. The farmers also make decisions on whether to farm or pursue other subsistence activities such as pastoralism based on assessment of the productivity versus energy costs. The farmer's decision-making is influenced by the three interrelated aspects of the Belief-Desire-Intention (BDI) model (Özerol and Bressers 2017; Balke and Gilbert 2014). The farmers' motivation in farming is to produce sufficient crop yields to sustain their households, while their beliefs relate to their perceptions and interpretations of the environmental and socioeconomic conditions. Finally, their intentions are guided by the resources they have available to them such as labour, access to land, and ability to manage water. Studies conducted by Özerol and Bressers (2017) have shown that the alignment of farmers within the BDI model differ between households and can result in variation in farmer decision-making in response to environmental changes.

The agents' objective is to farm a number of fields to meet the household's energy requirements, given an uncertain water supply and variable labour availability (Figure 32). The reason for this is so that the farmers are able to produce enough from agriculture to sustain the household even during times of resource scarcity. In cases where the productivity drops due to water stress because of low soil moisture, the agents make the decision to increase the area planted to increase productivity, or to develop canals to improve water availability. The different scenarios require different levels of energy and the farmers take into consideration the energy costs required for the different choices. The agents adapt their behaviour based on decision-making heuristics, and consider the expected water availability, previous water flows, yields, and the viability and attractiveness of alternative subsistence activities such as pastoralism. The farmers also consider their neighbours' behaviour, such that if a majority of the nearest farmers are engaging in farming this affects the likelihood of the agent also engaging in farming. The heuristics used by the agents to determine the alternative activities and effect of social norms are represented in a decision tree (Figure 33).

Social norms play a role in decision-making with farmers modelled to have a preference for farming over other subsistence activities, with traditional perspectives emphasised over economic profit maximisation strategies. Spatial aspects play a role as agents make decisions on where to place fields and when to expand or contract fields based on water availability, and on the proximity to other fields and canals. The decision on how many fields to farm is influenced by the memory of past yields and previous water availability as well as the household's energy needs based on the household size.

Uncertainty is not explicitly included in the agent's decision rule, but agents consider uncertain situations by taking previous yields or water availability as predictors of future situations. The agents consider whether or not to farm based on whether the previous year was a wet or dry year and the past yields. If agents suffer a series of dry years with poor water availability and yields then their preference for alternative activities increases.

5.2.2.3 Learning

There is no individual or collective learning included in the decision model. The agents do not change the decision-making rules.

5.2.2.4 Individual sensing

The farmers know about their energy/labour levels, the number of fields under cultivation, and the viability of subsistence activities; in addition, in hindsight the agents know the yield and energy used to build fields and canals. The agents are assumed to know the values of the relevant variables and they do not carry out any activities to receive this information. The spatial scale of sensing is global, and farmers do not know the state variables of other farmers, but can sense the subsistence activities that other farmers are engaged in. The costs of cognition and information gathering are not included in the model.

5.2.2.5 Individual prediction

The farmers make no predictions.

5.2.2.6 Interaction

The interactions between agents are mainly indirect and mediated by the environment with most interactions only through water use and extraction. However, the agents are able to sense the subsistence activities of other farmer households. The agents can make decisions on whether or not to farm based on the activities of their neighbours.

5.2.2.7 Collectives

The model contains no collectives.

5.2.2.8 Heterogeneity

There is no heterogeneity of agents, and all agents begin at a similar level of decision-making. The agents begin with the same set of decisions and can only alter their own actions but cannot alter the fundamental model decisions.

5.2.2.9 Stochasticity

The climate varies throughout the year and results in variations in water flow and soil moisture. Over time, the climate varies from year to year based on randomised probabilities of wetter or drier conditions.

Within the farmer households, the number of inhabitants per household varies randomly from an average. Agents are modelled based on fuzzy decision-making rules (Giusti and Marsili-Libelli 2015) such that given certain conditions of water stress the agents make decisions on whether or not to expand fields, build canals or choose between farming and alternative activities.

5.2.2.10 Observation

Data is collected every year on:

1. The number of fields used by the farmers and the number of fields irrigated.
2. Soil moisture, net erosion and vegetation biomass
3. Number of households and inhabitants, farmer crop yields and energy gained, energy cost of farming, and energy stores

4. Number of farmers engaging in farming or changing to other subsistence activities

The data is compared between the varied environmental scenarios as well as to other scenarios of alternative activities and the use of irrigation vs rain-fed agriculture, thereby highlighting the implications of these scenarios on the resilience of the irrigation system. In addition, the data outputs are used for sensitivity analysis to assess the model's ability to respond to variations in parameters.

5.2.2.11 Emergence

The key results emerging from the model are patterns of field use and expansion of the field system over time, and result from farmers' decisions in response to different climate conditions and scenarios of social norms and alternative subsistence activities.

5.2.3 TIME-MACHINE Details

5.2.3.1 Implementation Details

The model is implemented in Windows 7 using the NETLOGO platform version 5.2.1. The model is implemented through the biophysical entities and the farmer household agents. The biophysical entities are implemented at patch level where soil moisture changes, soil erosion and vegetation biomass interact through the functions of rainfall, temperature and soil depth (see sections above). The farmer household agents contain information about their energy stores, energy needs, energy costs of agricultural activities, the fields cultivated and irrigated and yields obtained. At each time step (each time step representing one month), the farmer households make decisions on whether or not to plant crops, tend crops, and harvest, as well as on whether or not to rely on rain-fed agriculture or to irrigate crops. At the end of each year, farmer households compare their yields to the ideal yields of alternative subsistence activities. If after 12 instances (where 12 instances equal 1 year) a famer notes that the alternative activities provide better returns, then that farmer switches to an alternative subsistence strategy (Figure 33). This aspect of decision-making also interacts with social norms, where there is a 50% probability that having neighbouring agents engaged in farming encourages farmer agents to stay in agriculture, but for the other 50%, the agents leave the system to engage in the alternative subsistence activities.

5.2.3.2 Initialisation

The model world of the Engaruka irrigation system is initialised with five farmer households that have an initial energy store, a number of inhabitants, and monthly energy needs (energy use person^{-1} month^{-1}). Initial conditions for state variables in each grid cell (elevation in metres above sea level, soil-depth in metres, and angle of slope) are derived from DEMs and from archaeological excavations and surveys of the test site, with ethnographic evidence from analogous farming systems providing information on the range of individuals per households, social norms that influence the use of subsistence activities, and decisions for the use of irrigation. The model parameters, their dimensions and default values are described in Table 8 below.

5.2.3.3 Model Inputs

Input data for processes that change over time include a 109 year CRU time series for rainfall and temperature data (Harris *et al.* 2014). The elevation data was obtained using a digital elevation model, the ASTER GDEM used is a product of METI and NASA as discussed in Chapter Two (NASA_JPL 2012; NASA_LP_DAAC 2011).

Table 8: Model Parameters and Initial values

Parameter	**Explanation**	**Model initial/ default value**
Hydrological/Soil moisture dynamics		
ΔSm	The change in soil moisture(mm month^{-1})	> 0
i	Infiltration depth (mm month^{-1})	> 0
r	Monthly rainfall (mm month^{-1})	≥ 0
R	Annual rainfall (mm a^{-1})	462

Parameter	Explanation	Model initial/ default value
r_c	Runoff coefficient (dimensionless constant)	0.18
I_a	Initial abstraction (mm)	8.080
S_{max}	Soil maximum storage (mm)	0.395
q	Runoff (mm)	≥ 0
PET/PE_m	Monthly potential evapotranspiration (mm month^{-1})	≥ 0
m	months	1 - 12
N_m	Monthly adjustment factor related to hours of daylight for the month being calculated (hours)	1
I	Annual heat index computed from the *j* monthly heat indices, where *j* is month 1 - 12	110.231
N	Number of days in the month (days)	30
L	Average day length (hours)	12
j_m	Monthly heat index	≥ 0
T_m	Monthly mean temperature (°C)	≥ 0
a	Empirical coefficient (dimensionless)	2.436
Sediment transport dynamics		
E_D	Diffuse erosion by un-concentrated overland flow (mm)	≥ 0
k_e	Diffuse erodibility factor (dimensionless)	0.02 – 0.80
S	Slope (m^1 m^{-1})	≥ 0

Parameter	Explanation	Model initial/ default value
V_c	Vegetation cover (%)	≥ 0
Vegetation Dynamics		
ΔV_B	The change in vegetation biomass	≥ 0
V_B	Vegetation biomass (kgha^{-1})	≥ 0
R	Annual rainfall (mm a^{-1}) (Harris *et al.* 2014)	462
W	Soil water availability (mm)	≥ 0
k_w	Half saturation constant of specific plant growth and water or nutrient uptake (mm)	0.25
d	Plant specific loss of biomass due to mortality (yr^{-1}) (Grass = 0.9, tree = 0.4 (Van Langevelde *et al.* 2003)	0.75
Engarukan farmer decision-making		
Y_f	Actual yield per farmer household (kg ha^{-1})	≥ 0
H_f	Number of inhabitants within each household	≥ 0
A_p	Standard number of fields planted by a given household based on the number of household individuals	≥ 0
E_f	The energy required to maintain the field systems and covers the energy expenditure required for planting (E_p), tending crops (E_t), harvesting (E_h) and irrigating (E_{irr}) fields. Energy (MJ month^{-1})	≥ 0
Y_i	Ideal yield of the farmer household(kg ha^{-1})	≥ 0

Parameter	Explanation	Model initial/ default value
Cr_B	Crop biomass	≥ 0
K_y	Crop yield response factor (sorghum: 0.9)	0.9
PET	Potential Evapotranspiration (mm month^{-1})	≥ 0
AET	Actual Evapotranspiration (mm month^{-1})	≥ 0

5.2.3.4 Sub-models

Soil moisture Hydrodynamics

The hydrodynamics sub-model of the Engaruka irrigation system simulates changes in soil moisture, surface water flows generated and sediment transport. The soil moisture and runoff (q) of each cell is updated at each time step as a function of infiltration and evapotranspiration (ET) and soil depth. The change in soil moisture can be related to rainfall and evaporation; at each monthly time step, the rate of infiltration and evapotranspiration (ET) are determined to give the change in soil moisture (Davie 2008 58). The basic model is a simplified equation of change in soil moisture within each cell:

$$\Delta Sm = i - ET \qquad \text{Equation 12}$$

where:

$$i = (1 - r_c) \times r \qquad \text{Equation 13}$$

ΔSm represents the change in soil moisture(mm month^{-1}), i represents infiltration depth (mm month-1), r is the monthly rainfall (mm month^{-1}) and r_c is the dimensionless runoff coefficient. Infiltration depth (i), in mm, is a function of rainfall (r) and a constant runoff coefficient (r_c) where actual infiltration is assumed to be proportional to the rainfall using the proportional loss model (de

Ridder and van Keulen 1995, 59). The runoff coefficient is considered to be a proportion of the rainfall (Yu *et al.* 1998 655) since not all precipitation reaches the ground, where some is intercepted by the vegetation and lost through evaporation. The runoff coefficient varies based on the type of soils and the vegetation cover with less water infiltrating in bare soils as compared to those with vegetation cover (Nill *et al.* 1996, 28). If the amount of rainfall is greater than a threshold value i.e. $r > I_a$ then infiltration is possible. When $r > I_a$, where:

$$I_a = 0.05 S_{max} * R \quad \text{Equation 14}$$

I_a represents the initial abstraction (mm), S_{max} is the soil maximum storage (mm) and R is the annual rainfall (mm a-1). Initial abstraction (I_a) is the amount of water before runoff, such as infiltration or rainfall interception by vegetation. If the amount of rainfall exceeds the rainfall threshold, infiltration occurs and the soil moisture levels approach the saturation levels (S_{max}). The maximum soil storage or k-saturation is the theoretical maximum proportion of water the soils can store at a given time. It is a proportion of the soil volume/depth usually based on the soil storage from the runoff curve number equation (Wainwright *et al.* 2008, 968). Otherwise, if the rainfall is below this threshold value, then runoff (q) = 0; and infiltration is equal to the amount of rainfall i.e. $i = r$. Where:

$$q = r_c \times r \quad \text{Equation 15}$$

Q represents the runoff (mm), r is monthly rainfall (mm month-1) and rc is the runoff coefficient. In the model, the change in soil moisture is dependent on the amount of water that infiltrates the soil column. As the soils approach saturation, excess water generates runoff (q). When the soil moisture exceeds the maximum soil storage, the excess flows add to the generated runoff which flows downstream and settles at the lowest elevation. Runoff then has an influence on the transport of sediments across the landscape through erosion and transport via overland flows.

The monthly evapotranspiration (ET) is estimated using Thornthwaite's (1948) equation for potential evapotranspiration PE_m (mm) (Lu *et al.* 2005, 631):

$$ET/PE_m = 16N_m\left[\frac{10T_m}{I}\right]^a$$ Equation 16

where:

$$N_m = \left(\frac{L}{12}\right) * \left(\frac{N}{30}\right)$$ Equation 17

$$I = \sum j_m = \sum \left[\frac{T_m}{5}\right]^{1.5}$$ Equation 18

and:

$$a = 6.7 \times 10^{-7}I^3 - 7.7 \times 10^{-5}I^2 + 1.8 \times 10^{-2}I + 0.49$$ Equation 19

ET/PE_m represents the monthly potential evapotranspiration (mm month-1), m represents the months, N_m is the monthly adjustment factor related to hours of daylight for the month being calculated (hours), I is the annual heat index computed from the monthly heat indices (j_m), N is the number of days in the month (days), L is the average day length (hours), T_m is the monthly mean temperature (°C) and a is dimensionless Empirical coefficient. If the PET exceeds the monthly rainfall, then the actual evapotranspiration AET is constrained to the monthly rainfall amount instead. This allows for a realistic estimation of evapotranspiration rates. To prevent negative soil-moisture values, values below zero are set to the initial value of soil moisture related to very dry soils.

Sediment transport dynamics

The sediment transport sub-model of the Engaruka irrigation system simulates the erosion and deposition of the sediments across the landscape using a modified Musgrave simulation based on un-concentrated overland flow (Wainwright 2006; Zhang *et al.* 2002):

$$E_D = k_e * q^2 * S^{1.67} * e^{-0.07V_c}$$ Equation 20

where:

$$V_c = \frac{V_B}{765}$$ Equation 21

E_D represents the diffuse erosion by un-concentrated overland flow (mm), k_e is the dimensionless diffuse erodibility factor, S is Slope (m^1 m^{-1}) and V_c is vegetation cover (%) and V_B is vegetation biomass (kg ha^{-1}). As runoff is generated, the water erodes the soil, transporting sediments downstream. The ease with which particles are eroded is dependent on the slope (S), runoff (q), type of vegetation cover (V_c) and the erodibility factor (k_e). The erodibility factor is dependent on the type of vegetation cover as different types of vegetation have different erodibility with bare ground having higher erodibility as compared to tree, grass or crop cover (Nill *et al.* 1996). As the sediments are eroded by the action of runoff, they are transported downslope and deposited once the flows lose velocity or they have reached the lower elevations. The eroded and deposited sediments then contribute to the changes in soil depth and soil fertility.

Vegetation dynamics

The vegetation sub-model simulates the dynamics of vegetation growth across the landscape. There are three types of vegetation based on the savannah model: trees, grass and crops. The vegetation dynamics are influenced by the soil moisture. In the model of the Engaruka irrigation system, the initial vegetation biomass is set to the carrying capacity as estimated in relation to annual rainfall (Wainwright 2006, 97):

$$V_B = 2500 + 5R \qquad \text{Equation 22}$$

The trees are dominant in the higher elevations and at steeper slopes of the escarpment, while the lower elevations and gentler slopes display a mix of trees and grass. This is based on existing vegetation mapping of the region and field observations (Ryner *et al.* 2008, 585). In addition, at the base of the escarpment the vegetation is dominated by crops in stone-bound fields that form the extensive irrigation system. The changes in vegetation biomass can be estimated using a simplified function of the soil water availability based on Walker's method (Moreno-de las Heras *et al.* 2015; Rietkerk *et al.* 2002).

$$\Delta V_B = \frac{W}{W + k_w} * V_B - dV_B \qquad \text{Equation 23}$$

ΔV_B represents the change in vegetation biomass, V_B is vegetation biomass (kg ha^{-1}), R is the annual rainfall (mm a^{-1}), W is soil water availability (mm), k_w is the half-saturation constant of specific plant growth and water or nutrient uptake (mm) and d is plant specific loss of biomass due to mortality (yr-1). Where changes in the biomass are a function of the soil water availability (W), a half saturation constant (k_w) and the plant specific mortality (d).

Engarukan farmer decision-making and management

The Engarukan farmers within the model engage in a series of simple behaviours that relate to agriculture and the development of the irrigation system as outlined above. The farmers' decision-making and management are related to the agricultural returns which depend on the crop yields achieved, the amount of land utilised by each household, and the cost of farming incurred. The following factors all have a role to play in the development of the Engarukan irrigation system: rainfall availability and variability, farmer response to these changes such as terracing and irrigation, labour costs, viability of alternative subsistence activities and the influence of neighbours in decision-making.

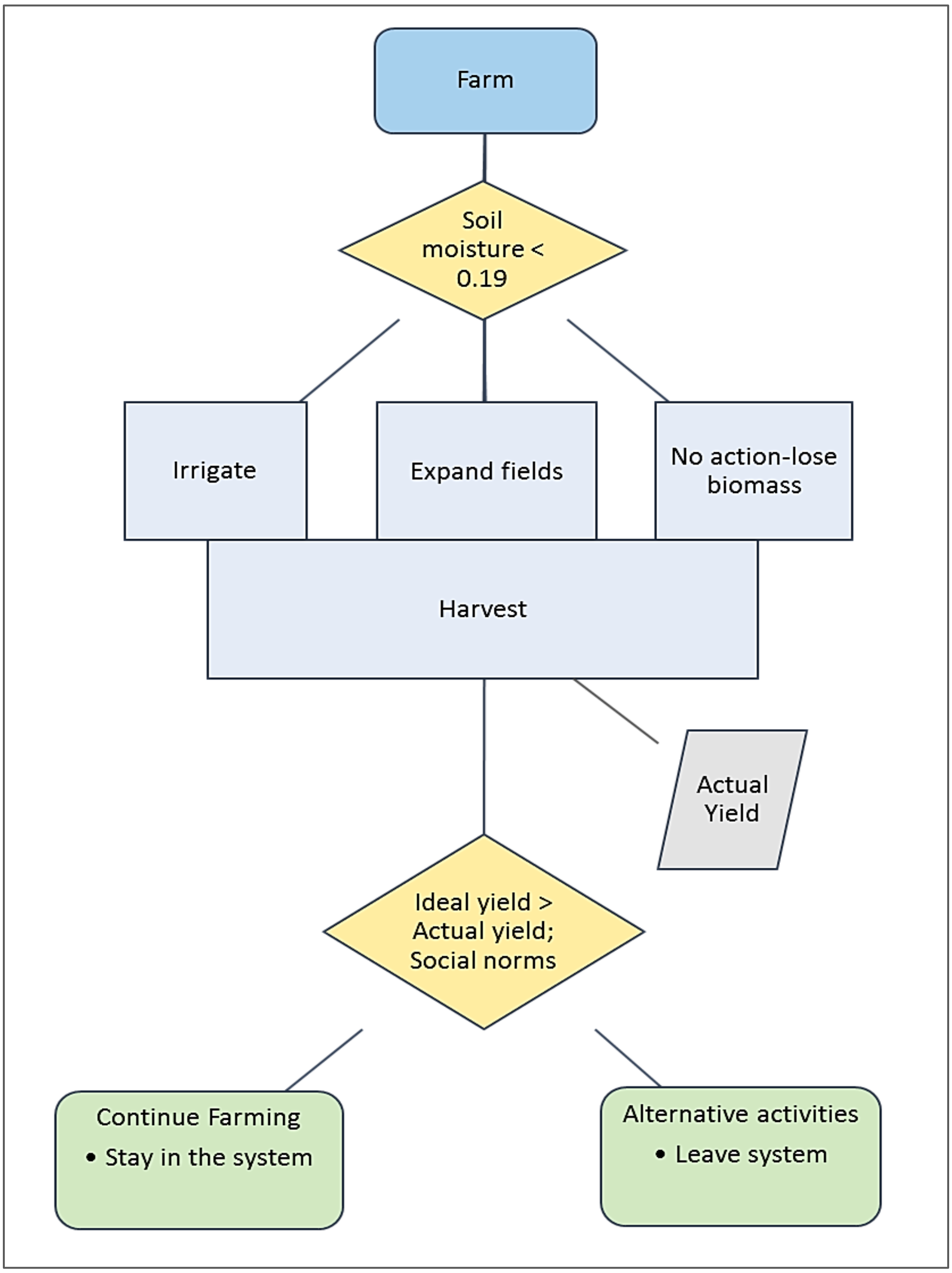

Figure 33: Farmer household decision-making tree outlining the choices involved for both rain-fed and irrigation agriculture where farmers must manage soil-moisture for successful crop production and are influenced by two scenarios of ideal yields from alternative subsistence activities and social norms that affect whether they stay in the system or leave.

As outlined in section 5.2.2.2 above, the farmer households prioritise subsistence agriculture and are able to store surpluses for use during non-productive periods; however, the farmers do not use these surpluses for commercial purposes. This is because, while there is evidence from other analogous communities that intensification can be driven by the need for trade or to provide surpluses for ruling elites (Davies 2015; Håkansson 2008), there is limited evidence of such trade connections within the Engaruka landscape and no evidence of social stratification. In addition, there could be a number of other reasons for the farmers to develop the irrigation system such as the need to increase production to meet growing population demand and for the purposes of soil and water conservation (Davies 2015; Stump 2013; Widgren 2010). The model therefore focuses on farmer production of subsistence resources.

The farmer's yields are expressed in terms of energy as the primary objective is to obtain sufficient subsistence resources as outlined below:

$$Y_f = E_G - E_f \qquad \text{Equation 24}$$

$$E_G = \frac{V_B}{2} \qquad \text{Equation 25}$$

Farmer decision on the standard number of fields to plant is based on the number of inhabitants per household:

$$A_p = \frac{H_f}{2.5} \qquad \text{Equation 26}$$

Where the energy costs of maintaining the farms are determined by the area planted and the energy expenditure, while the energy gained from the food crop is a function of the crop biomass:

$$E_f = E_p + E_t + E_h + E_{irr} \qquad \text{Equation 27}$$

where:

$$E_p = A_p * H_f * 0.05 \qquad \text{Equation 28}$$

$$E_t = A_p * H_f * 0.1 \qquad \text{Equation 29}$$

$$E_h = A_p * H_f * 0.3 \quad \text{Equation 30}$$

$$E_{irr} = A_p * H_f * 0.1 \quad \text{Equation 31}$$

Y_f represents the actual yield per farmer household (kg ha^{-1}), H_f is the number of inhabitants within each household, A_p is the standard number of fields planted by a given household and E_f represents the energy required to maintain the field systems and covers the energy expenditure required for planting (E_p), tending crops (E_t), harvesting (E_h) and irrigating (E_{irr}) fields (kg). The amount of energy stored is a function of the energy gained, monthly energy needs and the energy costs of farming.

The crop yield (Cr_B) is estimated using the FAO (2002) equation for crop yield response to water availability The FAO crop model differs from the Walker's method in that the FAO method relies on the use of evapotranspiration rates to determine changes in crop biomass yield, while the Walker's method utilises soil moisture availability (see sections above). In addition the crop yield response factor (K_y) values for different crops such as sorghum have been estimated and found to effectively estimate yields (FAO 2002):

$$\mathrm{Y_i} = Cr_B - Cr_B * K_y\left(1 - \frac{AET}{PET}\right) \quad \text{Equation 32}$$

Y_i represents the ideal yield of the farmer household (kg ha^{-1}), Cr_B is Crop biomass, K_y is the crop yield response factor, PET is Potential Evapotranspiration (mm month-1) and AET is the Actual Evapotranspiration (mm $month^{-1}$). The historical Engarukan farmers allocate labour to farming activities and decide at the end of each year if they need to plant more fields or move to a different economic activity that takes them out of agriculture. However, this decision is not immediate and is dependent on whether or not the farmers decide if they will allocate some of their labour to alternative subsistence activities (such as pastoralism or trade or hunting) in order to improve their overall returns (Becu *et al.* 2003, 324). The off-farm returns are calculated as being equal to the ideal agricultural yields and the farmers are primarily predisposed to pursuing agriculture as compared to other activities. The farmers compare their total energy gained to that of the ideal yields. If their actual yields are less than the ideal yields for a total of five years, the farmers can decide to switch to the alternative subsistence activities or leave the system.

5.2.4 TIME-MACHINE Model Sensitivity Analysis

One of the main challenges of modelling the historical Engaruka system is the scarcity of data on the study area. To assess the model's sensitivity to changes in model parameters, global sensitivity analysis was conducted using the NetLogo BehaviorSpace and R 3.3.3 to explore the various model parameters in a systematic way. Selected input parameters were varied and the model was iterated over 60 time steps. This was in order to explore the model behaviour for varying parameters and how they affect model outputs in order to see which parameters had the greatest influence on model outputs. The outputs were then graphically visualised in R using ggplot (Wickham 2009) to assess the sensitivity of the model to variations in model inputs. Model results were then compared to existing literature where possible to assess the alignment of model processes with real-world dynamics. Due to computational constraints, global sensitivity analyses were split into two: environmental parameters and farmer-household parameters (Table 9).

Table 9: Model parameters used for Global Sensitivity Analysis in BehaviorSpace

Parameter	**Min value**	**Max value**	**Varied by**
Environmental parameters			
Runoff coefficient (r_c)	0.1	1.0	0.1
Erodibility coefficient (k_e)	0.1	1.0	0.1
Half saturation constant (k_w, mm)	0.2	1.0	0.2
Plant mortality (d, yr^{-1})	0.2	1.0	0.2

Parameter	Min value	Max value	Varied by
Farmer-household parameters			
Farmer households No.	5	20	5
Number of inhabitants within each household (H_f)	2	20	2
Energy use (person^{-1} month^{-1})	0.5	5	0.5

Exploratory factorial analysis of the data for the model shows that the differences in runoff coefficient had the greatest influence on the simulated soil moisture recharge (Figure 34). Higher runoff coefficients resulted in lower soil moisture recharge and higher runoff. This relates to real-world studies that have found that bare soils have a higher runoff coefficient as compared to those with vegetation cover, with patches with tree cover having the lowest runoff coefficients (Nill *et al.* 1996). Cumulative soil moisture decreased as the runoff coefficient increased while the erodibility coefficient had little effect on the soil moisture. At lower runoff coefficient values more water infiltrated resulting in higher soil moisture, while as the runoff coefficient increased the soil moisture values decreased. As runoff coefficient values increased, the cumulative soil moisture dropped before levelling out. This is because as the runoff increases less water is infiltrating and contributing to soil moisture. The lower soil moisture values coincide with expected values for areas with vegetation cover and ground with shallow slopes, as would be expected for areas of agriculture. The model therefore uses initial runoff coefficient values of 0.2 to reflect values that would be found in vegetated areas including agricultural field systems that would be covered in crop vegetation cover.

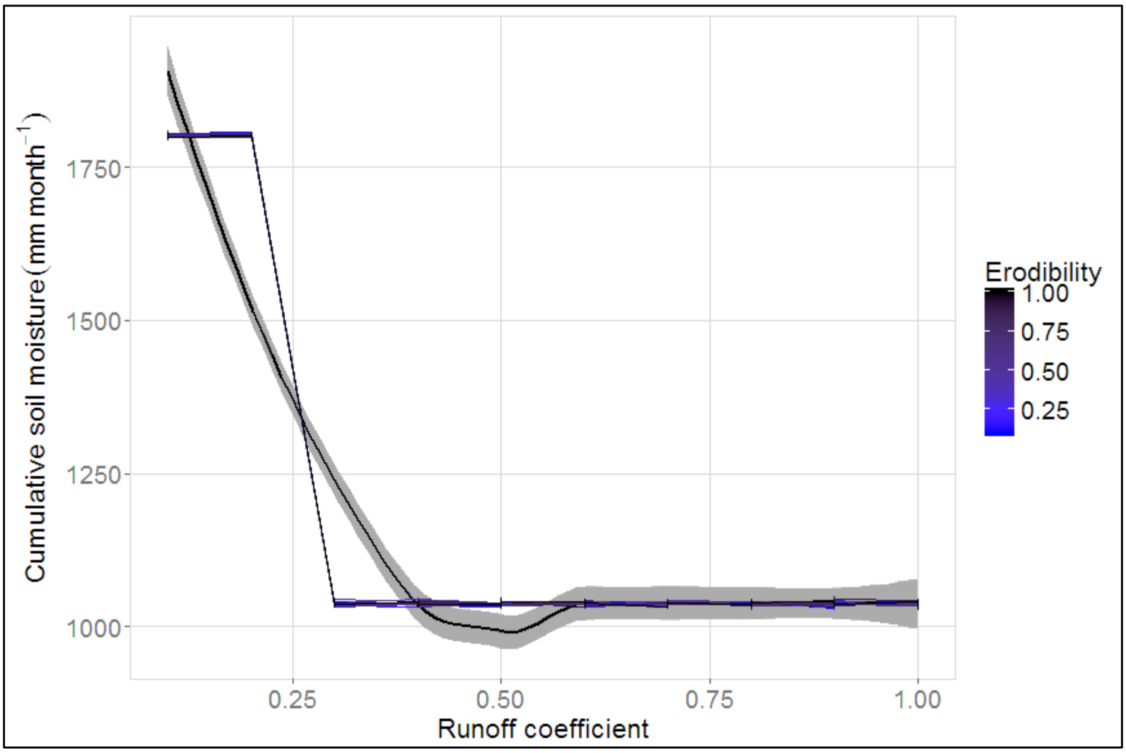

Figure 34: Cumulative soil moisture (mm month^{-1}) plotted against increasing runoff coefficient values and grouped according to the interacting effect of changing erodibility coefficient values

The erodibility coefficient had little to no interacting effect on the soil moisture recharge (Figure 34) however, because as the erodibility coefficient increased cumulative net erosion increased (Figure 35). In addition, the runoff coefficient had a notable interacting effect on net erosion with higher runoff coefficients corresponding with higher cumulative net erosion. The increasing erodibility coefficients can be related to changes in vegetation cover with higher erodibility related to lower vegetation cover. The variations in the erodibility coefficient and vegetation cover influenced erosion and interacted with runoff, resulting in increased erosion where erodibility coefficients were higher or where vegetation cover was low, while lower runoff and higher vegetation cover resulted in lower erosion rates. Thus as the erodibility increased, the cumulative net erosion increased and resulted in greater erosion across the landscape.

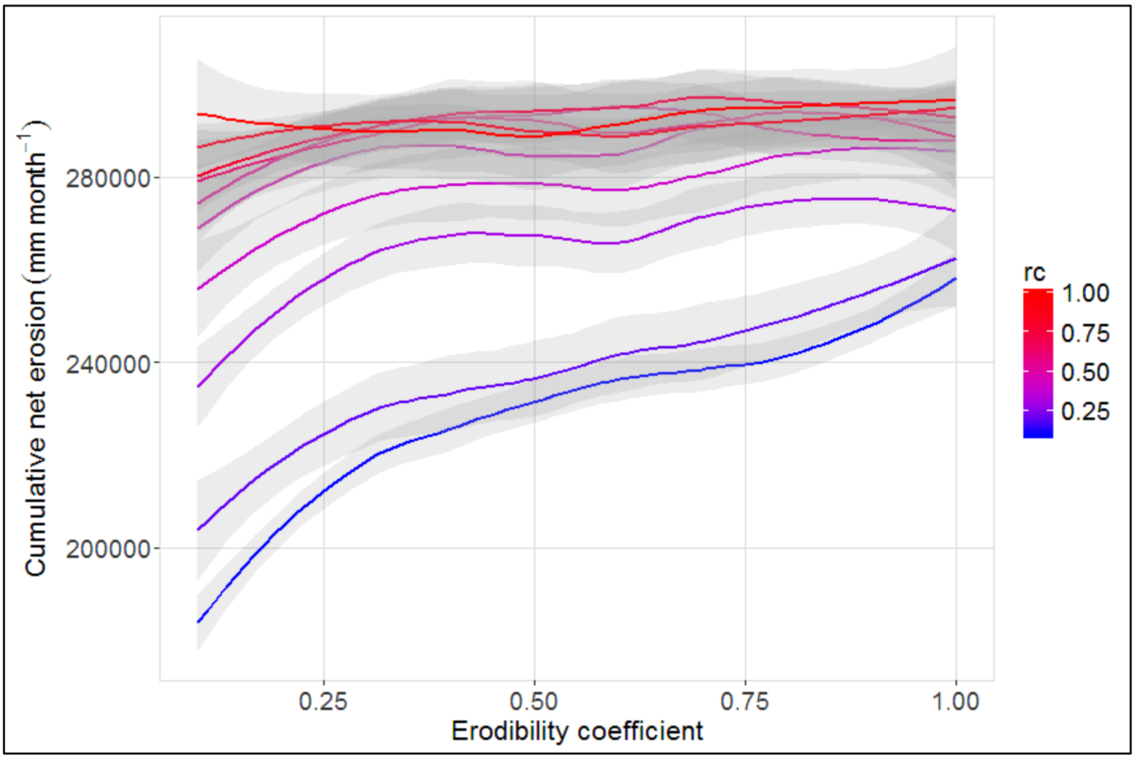

Figure 35: Cumulative net erosion (mm month^{-1}) plotted against increasing erodibility coefficient values and grouped according to the interacting effect of increasing runoff coefficient values. The shaded areas show the uncertainty inherent in estimates of the true relationship between the outputs and the predictor variables.

As the values for the erodibility coefficient increased the cumulative net erosion increased; while the runoff coefficient also affected erosion with increases in runoff coefficient resulting in higher net erosion (Figure 35). The interacting effect of runoff coefficient was most noticeable at lower runoff coefficient values, with lower runoff coefficients resulting in lower cumulative erosion while at higher values the effect of the runoff coefficient became less distinct for different runoff values. This is because of the limits on material available to be eroded, such that at higher runoff coefficients material is eroded faster, with erodible material removed from the system quickly. However, at lower runoff coefficient values the increase in net erosion is more noticeable with the increasing erodibility coefficient. This relates to the relationship described in Equation 20 above that shows the interacting effect of runoff and erodibility on erosion.

Results of the sensitivity analysis show that as the half-saturation constant values increased, the vegetation biomass decreased while the plant mortality constant had less of an effect on the vegetation biomass (Figure 36). The vegetation biomass was greatly influenced by the half-saturation constant while the plant mortality constant had a smaller effect on vegetation biomass.

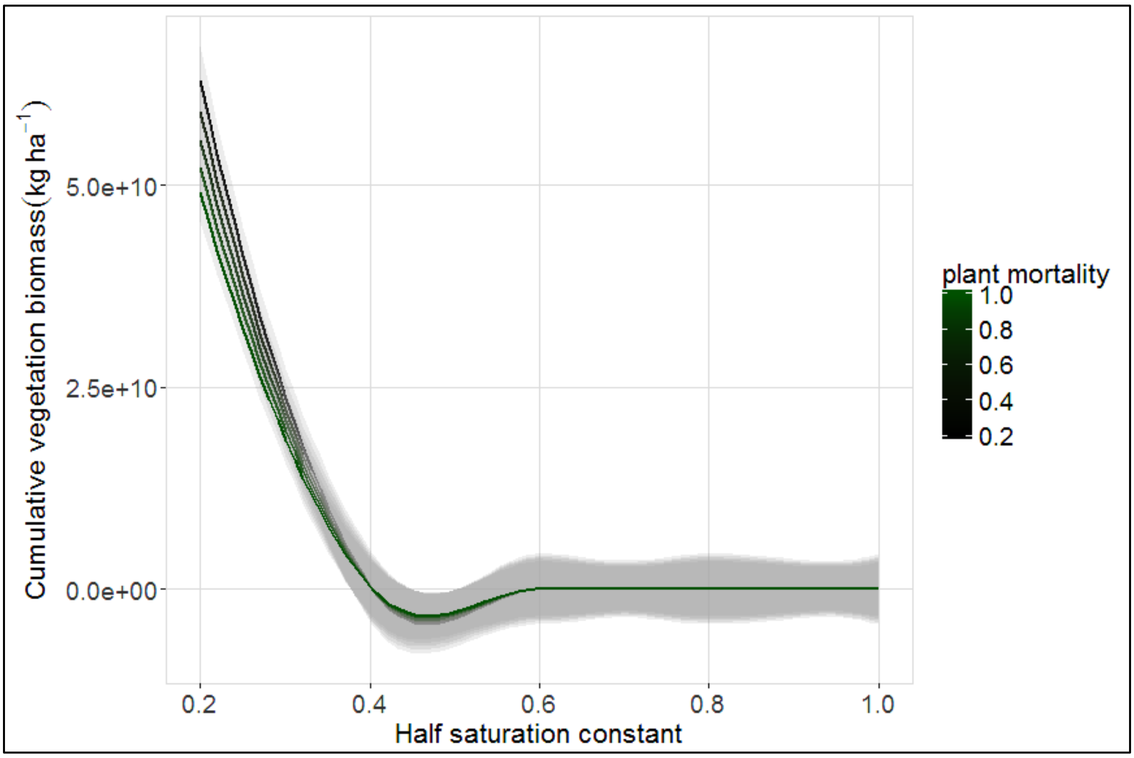

Figure 36: Cumulative vegetation biomass (kg ha-1) plotted against increasing half-saturation constant values and grouped according to the interacting effect of increasing plant mortality values. The shaded area shows the uncertainty inherent in estimates of the true relationship between the outputs and the predictor variables.

Vegetation biomass was greatest at lower half-saturation constant values, but as the constant increased, vegetation biomass decreased. The half saturation constant relates to the water and nutrient uptake by plants (Rietkerk and Koppel 1997). This is due to the effect of the half-saturation constant on water availability as described in Equation 23 above; with increases in the half-saturation constant resulting in inverse increases in water availability for biomass production. In addition, plant biomass stabilises at higher half-saturation values because plants and animals tend to acquire resources at lower concentrations which relate to the low half-saturation constant values (Mulder and Hendriks 2014, 162). At lower values for half-saturation constant the interacting effects of plant mortality on vegetation biomass were more noticeable (Figure 36). The effect of the plant mortality constant was greater at lower values for the half-saturation constant because when water availability and soil moisture are at adequate levels for plant growth, the effect of plant mortality has greater influence.

The total number of fields planted was affected by the number of farmer households and the number of individuals in each household (Figure 37). As the number of farmer households increased the area planted increased with an interacting effect whereby the increase in the number of individuals in a household resulted in a higher number of fields planted.

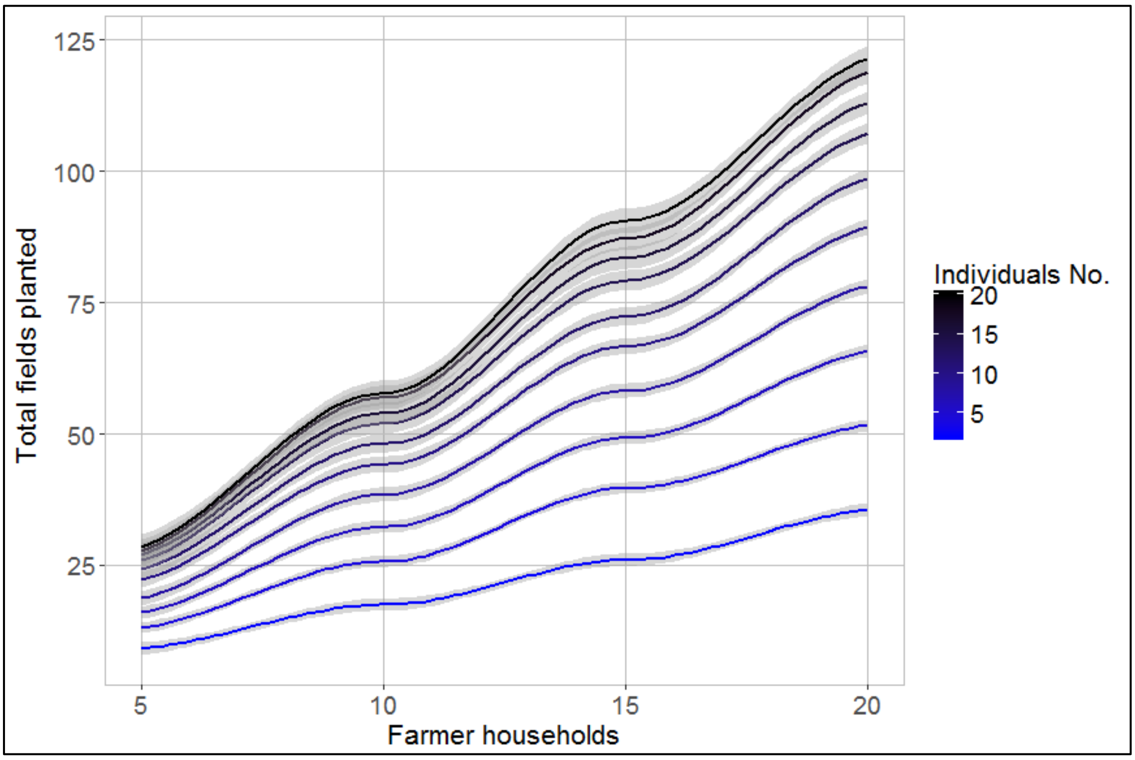

Figure 37: Total fields planted plotted against increasing number of farmer households and grouped according to the interacting effect of increasing number of inhabitants per farmer household. The shaded areas show the uncertainty inherent in estimates of the true relationship between the outputs and the predictor variables.

The area planted is dependent on the number of household inhabitants (Equation 26) so the increase in the number of inhabitants results in an increase in the total number of fields planted. And an increase in a number of households leads to an increase in the number of total inhabitants which then results in a corresponding increase in total area planted.

The number of inhabitants in a farmer household and the amount of energy used by each individual affected the amount of energy that was stored by the household (Figure 38). Energy use per person and number of inhabitants per household interacts directly with the energy store in the model and therefore affects how much energy each household was able to store.

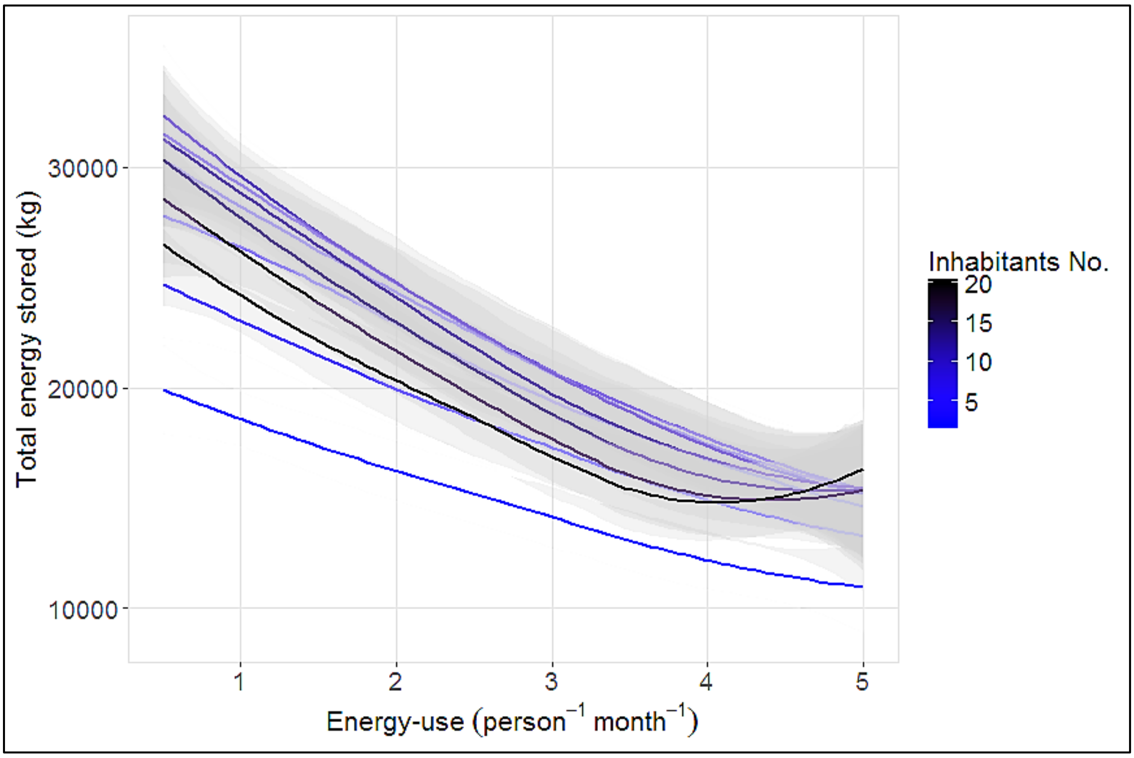

Figure 38: Total energy stored plotted against increasing energy use per person per month and grouped according to increasing numbers of inhabitants. The shaded area shows the uncertainty inherent in estimates of the true relationship between the outputs and the predictor variables.

As the energy use of the individuals in each households increase, the amount of energy they can store declines (Figure 38). The number of individuals in a household also affects the energy stored as the number of individuals determines the number of fields they can plant and thus the energy harvested. However, at higher numbers of individuals the effect of energy use on total energy stored has a greater effect where the differences in number of individuals are not distinctly differentiated except where individuals in a household numbered five.

5.3 TIME-MACHINE Model Scenario Implementation and Analysis

The model was implemented under two primary model scenarios of rain-fed agriculture compared to irrigated agriculture. Under these two scenarios the model was further implemented under a series of eight scenarios combining environmental factors of climate and water availability and human factors in decision-making. These scenario implementations were designed to help understand how the different factors and the interaction of factors influenced the development and continued use of the Engaruka water-management system. In doing so, the model outputs can support our understanding of the resilience and sustainability of the system over time. Simulations were run over a period of 115 years to incorporate multi-decadal variability in climate and to explore the possible long-term effects of farmer-household decisions and social norms on the continued use of the system.

5.3.1 Rain-fed and Irrigated agriculture

As outlined above, the farmer-households make decisions on farming and respond to soil moisture stresses that influence crop productivity (Figure 33). These responses include constructing more fields to increase crop biomass and irrigating fields to improve soil moisture, while taking no action results in a loss of biomass. The model makes the assumption that there are no limitations to water and soil moisture availability with distance from the water sources. Given the archaeological evidence of the irrigation infrastructure, the use of irrigation to supplement the soil moisture needs for the system is inferred (Stump 2006a). However it is unclear simply from interpreting the archaeological evidence if the irrigation measures were the primary action or if they were intended to supplement rain-fed agriculture. The model therefore simulates two primary scenarios one in which rain-fed agriculture is combined with supplemental irrigation, and the other scenario describes a fully irrigated agriculture system.

5.3.1.1 Rain-fed agriculture with supplemental irrigation (Rain-fed-SI)

Under the scenario of rain-fed agriculture with supplemental irrigation (Rain-fed-SI), the farmer households prioritise rain-fed farming and respond to soil moisture stresses primarily by expanding their fields (50% of the time) with additional responses being that they either use supplemental irrigation (25%) or have no adaptation response and lose crop biomass (25%). The use of rain-fed agriculture with supplemental irrigation while rarely utilised in East African smallholder farming systems (Rockstrom 2000, 281), could possibly represent the responses employed and the archaeological evidence of irrigation infrastructure of the Engaruka system. Studies on supplemental irrigation show that it has the potential to improve soil moisture under constraints of low water availability (Rockström *et al.* 2010, 546; Oweis and Hachum 2006). Modelling the scenario of Rain-fed-SI is intended to demonstrate how the use of this agricultural practice could provide an explanation for the archaeological evidence of irrigation infrastructure and point to the adaptation practices employed.

5.3.1.2 Irrigated agriculture

Under the scenario of Irrigated agriculture, the farmer-households prioritise crop farming under irrigation and respond to soil moisture stresses primarily by irrigating the fields (50% of the time), with additional responses being that they expand their irrigated fields (25%), or have no adaptation response and lose crop biomass (25%). This simulation represents the conventional irrigation agriculture practices employed and inferred from the archaeological evidence at Engaruka (Stump 2006a; Sutton 1998).

The intention of simulating these two scenarios of Rain-fed-SI and Irrigated agriculture is to understand how the farmer responses under these different agricultural practices influenced the expansion of the field system and the impact on yields and energy expenditure. These two primary scenarios are then simulated under different scenarios of climate variability, response to alternative activities, and effect of social norms, all of which help to understand how these factors further influence the system's development and its resilience and sustainability.

5.3.2 Climate variability and water availability

The climate in Engaruka follows a bimodal rainfall pattern with two wet seasons and two dry seasons in a calendar year (Figure 39) (Harris *et al.* 2014; Jones and Harris 2008; Ryner *et al.* 2008). This seasonal variability results in variability in water availability and affects soil moisture recharge in soils. The climate variability scenarios modelled incorporate seasonal fluctuations that influence crop productivity and farmer-household decision-making. The primary environmental factor influencing agricultural production in semi-arid ecosystems in sub-Saharan Africa is rainfall availability and its variability over time (Biazin *et al.* 2012; Oweis and Hachum 2006; Critchley and Siegert 1991). By modelling the Engaruka system under the Rain-fed-SI and Irrigated agriculture scenarios with different climatic scenarios, we gain an understanding of how the historical system would have functioned under different conditions of precipitation and temperature.

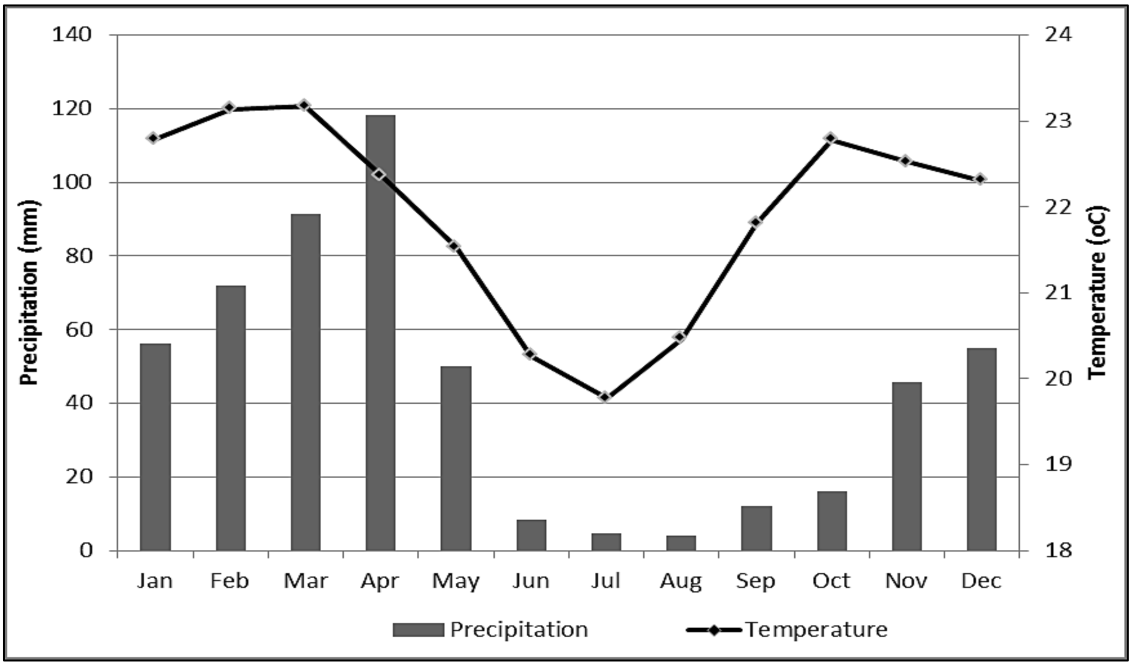

Figure 39: Mean monthly precipitation and temperature 1901 – 2009 for Engaruka, Tanzania, from the CRU time series high resolution gridded datasets (Harris *et al.* 2014)

5.3.2.1 TM-01 Current climate

In TM-01 Current climate, monthly rainfall and temperature values were maintained at the initial model conditions (Figure 39) based on the 100 year averages obtained from the CRU time series high-resolution gridded datasets 1901 -2009 (Harris *et al.* 2014). By modelling the system based on current climatic conditions we can assess the effect of contemporary climate on the Rain-fed-SI and Irrigated agriculture practices in response to these conditions and thus their applicability to modern systems.

5.3.2.2 TM-02 Long-term climate variability

In TM-02 Long-term climate variability, historical climate fluctuations are modelled from palaeoclimatic proxies (Figure 40), which show that the East African climate was much wetter than present conditions, albeit interspersed with long dry periods (Gelorini and Verschuren 2013; Verschuren *et al.* 2000). The Engaruka system is believed to have been in use between the 15th and 18th centuries CE which falls within a relatively wet climate period of the Little Ice Age (approximately 1270 -1850 AD) which was interspersed with periods of prolonged dry conditions (Verschuren *et al.* 2000).

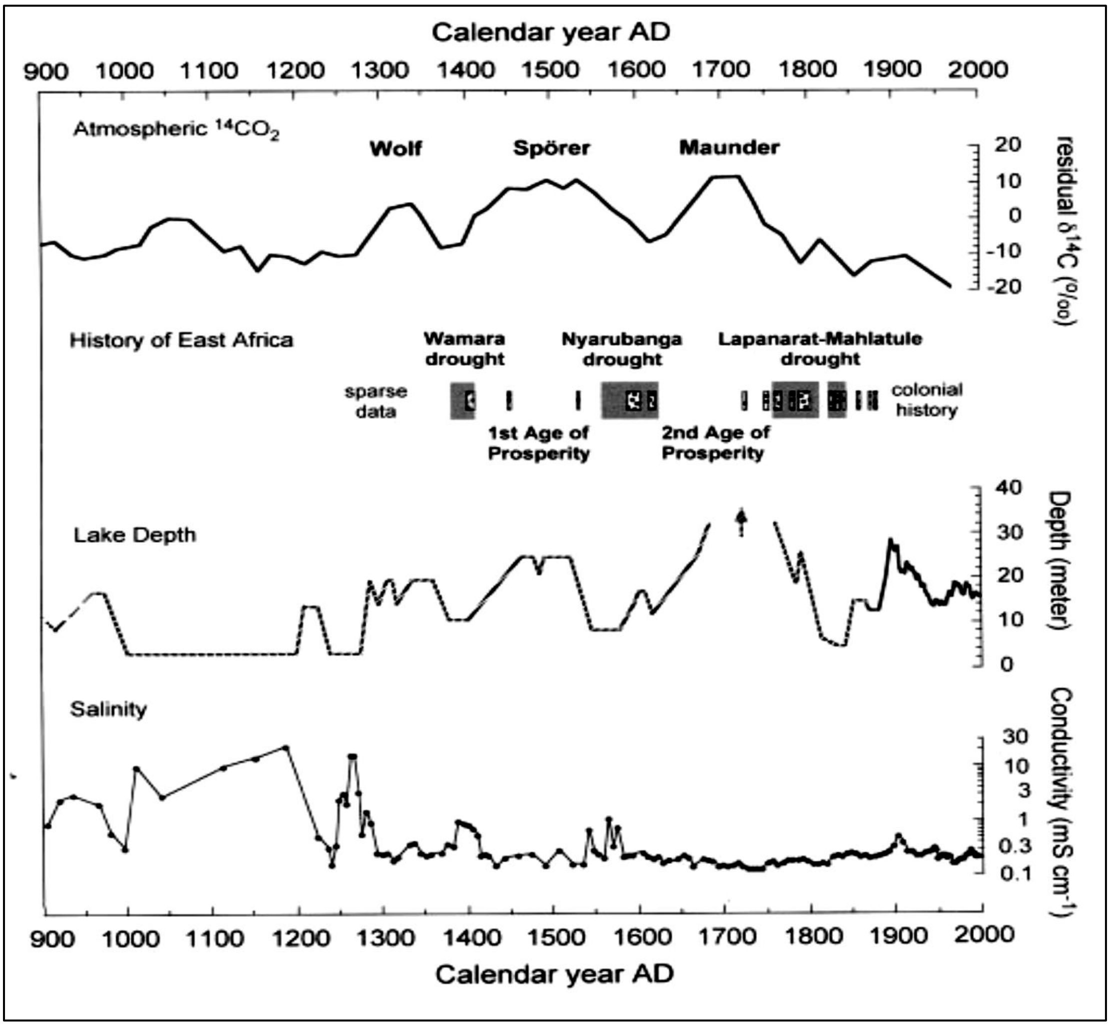

Figure 40: East African historical regional climate fluctuations modelled from palaeoclimatic proxies (Verschuren *et al.* 2000, 413)

TM-02 simulates these long-term climate fluctuations by incorporating relatively wetter conditions by increasing monthly rainfall by an arbitrary 20% and simulating drier conditions by reducing monthly rainfall by the arbitrary 20%. This simulation is intended to assess the effect of these decadal fluctuations in climate on the expansion and continued use of the system.

5.3.2.3 TM-03 Wetter conditions

In TM-03 Wetter conditions, the precipitation values were increased by an arbitrary 20% to model relatively wetter conditions. As outlined above, the Engaruka system's use falls within a period of relatively wetter climate which has a significant effect on soil moisture recharge. TM-03 simulates conditions of increased rainfall that results in increased soil moisture which in turn affects crop yields. In this way the effect of improved water availability for the expansion and continued use of the system under Rain-fed SI and Irrigated scenarios is assessed.

5.3.2.4 TM-04 Drier conditions

In TM-04 Drier conditions, the precipitation values were decreased by an arbitrary 20% to model the prolonged dry conditions. As outlined above, the Engaruka system's use falls within a period of relatively wetter climate interspersed by long dry spells (Figure 40). TM-04 simulates conditions of reduced rainfall resulting in decreased soil moisture which in turn affects crop yields. This simulation magnifies the decadal prolonged dry periods to assess the effect of the extreme dry conditions on the expansion and continued use of the system under Rain-fed-SI and Irrigated scenarios.

5.3.2.5 TM-05 Cooler and wetter conditions

In TM-05 Cooler and wetter conditions, the effect of temperature was incorporated with precipitation values increased by 20% and temperatures reduced by 0.8 °C. This is in order to simulate the effect of historically wetter conditions as well as incorporating the effect of temperature. Global surface temperatures have risen by 0.78° – 0.90 °C century^{-1} since 1901 (Blunden and Arndt 2016, 11). This increased temperature has an effect on soil moisture recharge by affecting evapotranspiration rates, in turn affecting crop yields where crops suffer increased water stress. Studies by Carleton and Hsiang (2016, 7) document the damaging impacts that temperature has on crop yields. In addition, increased temperatures negatively affect water use efficiency in agriculture through increased evaporation rates (Carleton and Hsiang 2016, 7; Wallace 2000). Given the combined impact of rainfall and temperature, TM-05 simulates relatively wetter and cooler conditions to assess if these climatic conditions facilitated the expansion and continued use of the Engaruka system under the Rain-fed-SI and Irrigated agriculture practices.

5.3.3 TM-06 Alternative subsistence activities

In TM-06 Alternative subsistence activities, the effect of alternative activities is simulated in order to assess the factors that could have led to the abandonment of the Engaruka system. As discussed above (Equation 32), the farmer-households agents compare their actual yields with theoretical ideal yields that equal those of alternative activities such as trade or pastoralism. These ideal yields represent alternative subsistence activities that could provide equal or greater returns than those obtained under agriculture. As discussed in the sections above, the farmers prioritise subsistence farming guided by the BDI model of decision-making (Özerol and Bressers 2017; Balke and Gilbert 2014) such that their motivation is to produce enough crop yields to sustain the households, which is dictated by the resources they have available to achieve this. The farmer-households are also able to perceive and respond to environmental and socioeconomic factors. The farmers decisions are also guided by bounded rationality such that they wish to optimize agricultural returns but have a limited perception of the environment and behavioural options (Schlüter *et al.* 2017, 27). Archaeological evidence from the Engaruka system shows no evidence of social stratification that would have had an overall influence of farmer choices in subsistence activities or that would show that they prioritised commercial agriculture. The TM-06 scenario simulates the farmer-households ability to perceive alternative subsistence activities that provide better yields and make the decision on whether to switch over. The decision on whether or not to switch is made once the farmer-households reach a perceived limit of instances in which the alternatives exceeded actual agricultural yields. The farmer-households who decide to make the switch continue to stay within the system but if they have no further motivation to return to farming i.e. actual yields from agriculture do not exceed ideal yields from alternative activities, they then eventually leave the system. The model makes the assumption that the costs of repairing the field system on their return would be equivalent to the costs of constructing and utilising the fields and therefore does not incorporate an additional cost to repairing the system on their return. This simulation is intended to facilitate our understanding of the patterns and timescales of farmer decision-making that could have affected the continued use of the Engaruka system under the Rain-fed-SI and Irrigated agriculture practices.

5.3.4 TM-07 Influence of Social Norms

TM-07 Influence of Social Norms, the influence of social networks is simulated to assess the effect of social norms on the farmer-households decision-making when presented with choices between agriculture and alternative subsistence activities. Studies show that farmers make decisions influenced by their peer group (van

Duinen *et al.* 2016, 340). The farmer-households therefore take into consideration the actions of other farmers. This simulation is based on the concept that individuals or households may want to conform to the more dominant decision within a community (Schlüter *et al.* 2017, 23). This means that while the community shows no social stratification whereby the farmers' practices are dictated by a social elite class, decisions taken by individual farmers are influenced by those of the majority of farmers around them. The social norms simulation is based on a probability that the farmers will prioritise farming if others are also engaging in it, and the probability determines the extent of the effect on farmer-households decisions to continue farming or leave. The TM-07 simulation is intended to determine the effect social norms will have on the decisions made by the farmer-households in choosing the alternative activities or continuing farming. In this way, the simulation facilitates our understanding of social factors that could have affected the continued use of the Engaruka system under the Rain-fed-SI and Irrigated agriculture practices.

5.3.5 TM-08 Population size effect

In TM-08 Population size effect, the influence of the number of farmer-households combined with social norms on a farmer's decision to continue farming or leave is modelled. As has been discussed above, the farmers might be influenced by social norms that govern the majority. The effect of this decision-making can be further influenced by the population size where having more households leaving or staying might have a bearing on the choices made by other households. The model simulations discussed above are based on a population of 20 farmer-households each made up of an average of eight household members based on estimates from studies on similar farming communities of the Pokot and Marakwet in Kenya (Davies 2010, 207). The number of households was then increased to assess the effect this would have on decision-making. The TIM-08 simulation therefore facilitates our understanding of the influence of population size on the continued use of the Engaruka system.

5.4 TIME-MACHINE Model Results and Discussion

The results of the model simulations provide information on the effect of the different agricultural practices of Rain-fed-SI and Irrigated agriculture on the continued use of the system given different scenarios of climate and human factors of alternative activities, social norms and population size, simulated for a period of 115 years.

5.4.1 Rain-fed vs Irrigated agriculture

The results of the model simulation show that under current climate conditions (TM-01), the Irrigated scenario resulted in higher yields per the number of fields planted as compared to Rain-fed-SI (Figure 41). The Irrigated scenario resulted in cumulative yields averaging 13,000 kg ha^{-1} over the 115 years period, while Rain-fed-SI produced yields of 10,000 kg ha^{-1}. In addition, fewer fields were planted under the Irrigated scenario at an average of 50 fields planted, as compared to the Rain-fed-SI scenario which averaged 90 fields planted. The returns from the use of irrigation are therefore evident where a smaller number of fields resulted in higher yields as compared to the Rain-fed-SI scenario. The benefits of irrigated agriculture on yields have been the subject of development agendas and research as a way to improve productivity without increasing the land area under agriculture (Stump 2010a; Wallace 2000). By utilising irrigation to improve soil moisture recharge, the farmer-households were therefore able to achieve higher yields per the area planted as compared to the scenario of Rain-fed-SI agriculture.

The field sizes simulated in the model landscape measured 900 m^2 per field such that if the farmer households were planting an average of 50 fields each year, this was covering an area of 45,000 m^2 in the Irrigated scenario, while under Rain-fed-SI the 90 fields covered 81,000 m^2. When compared to the archaeological evidence of the extent of the South Fields which covers 3.5 km^2 (Stump 2006b, 156) these represent only a small section of the entire field system. If farmers were utilising new field areas every year due to the incorporation of practices such as fallowing, the fields could have been expanded to cover the entire South Fields after 77 years for the Irrigated scenario, and 43 years for the Rain-fed-SI scenario. However, these values provide only minimum rates for the expansion of the system and do not incorporate factors such as the time it would take to accumulate soils in the sediment trap fields as discussed in Chapter Four. In addition, under the Rain-fed-

SI scenario, farmer-households were able to expand the area planted when utilising supplemental irrigation which would further reduced the time it would take to build fields that cover the entire South Fields as discussed below.

The model results also show that despite planting fewer fields, the Irrigated scenario had higher energy costs as compared to the Rain-fed-SI scenario. Despite planting fewer fields at an average of 50 fields, the Irrigated scenario exacted higher energy costs at an average of 2200 MJ a^{-1} as compared to the Rain-fed-SI scenario where the 90 fields planted resulted in energy costs of 1500 MJ a^{-1} (Figure 41). These higher energy costs of the Irrigated scenario can be attributed to the additional labour and energy required to construct and maintain the irrigation infrastructure under a fully irrigated system.

The scenario of Rain-fed-SI incorporates the idea of supplemental irrigation to improve soil moisture while resulting in lower energy costs. Under the scenario, farmer-households incorporate irrigation water when needed to maintain crop productivity. When the crops are affected by soil moisture stress and farmers decide to utilise supplemental irrigation, they apply irrigation water to all the fields planted. The results of modelling the Rain-fed-SI scenario under different climate conditions showed that when utilising supplemental irrigation, the total area planted doubled under supplemental irrigation (Figure 42).

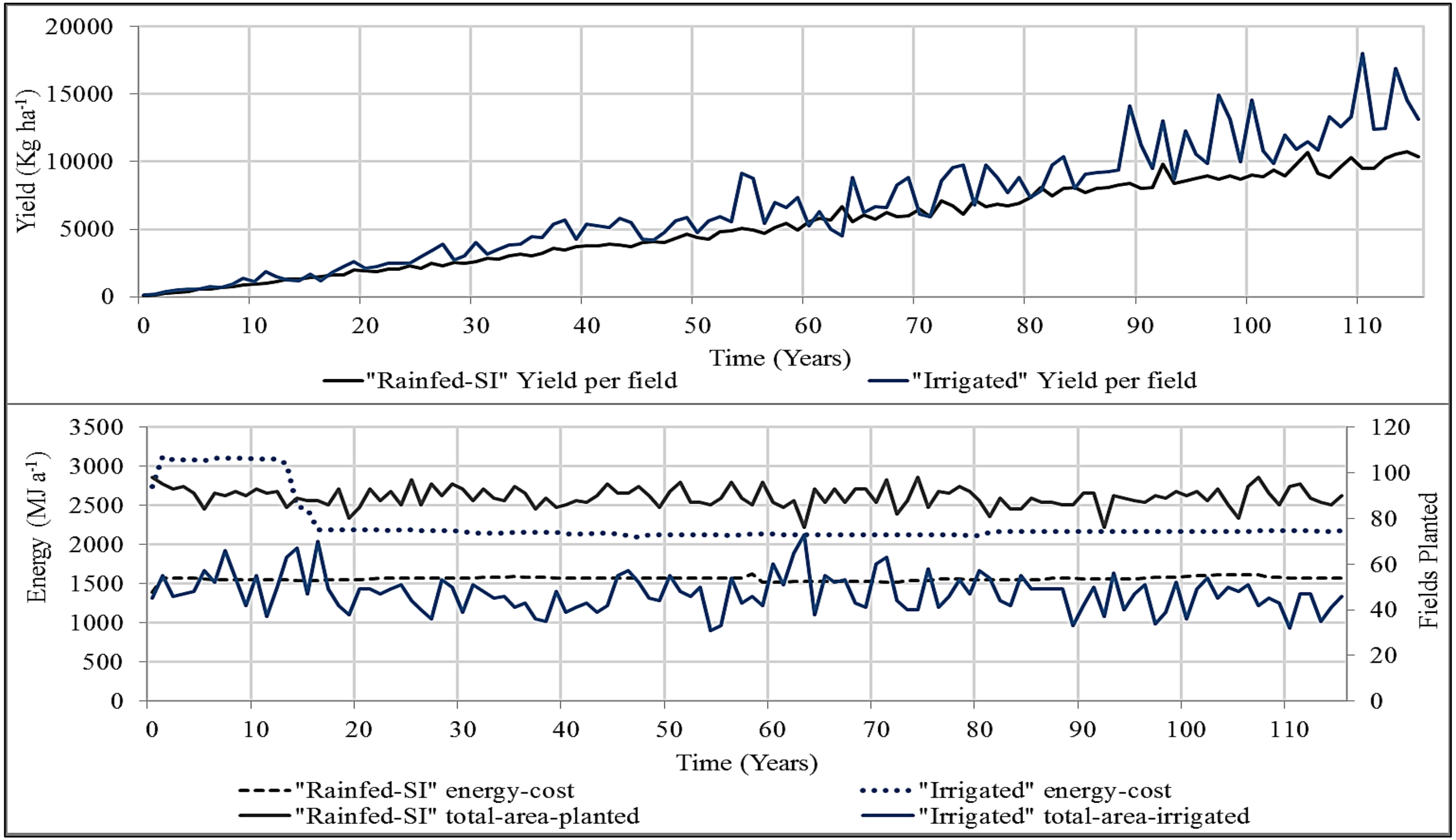

Figure 41: Yield (kg ha^{-1}) compared with the energy cost (MJ a^{-1}) and the number of fields planted over time by the farmer-households for scenarios of Rain-fed-SI and Irrigated agriculture under current climate conditions (TM-01)

Under current climate conditions simulated under TM-01, the farmer-households planted slightly fewer fields than the standard area planted of 105 fields at 90 fields but when supplemental irrigation is applied the number of fields increase to 207 fields planted (Figure 42). The highest number of fields planted was shown under TM-04 simulating drier conditions with the standard area increasing to 111 fields while the total area planted was 93 and increasing to 219 fields when using supplemental irrigation. Under TM-02 simulating for long-term climate variability, the standard number of fields was 104 fields and farmer-households planted 90 fields which increased to 204 fields under supplemental irrigation. When simulating for wetter conditions in TM-03, the standard number of fields was 106 fields while the total area planted was 93 fields and 208 fields under supplemental irrigation. Under cooler and wetter conditions simulated in TM-05, the standard area for planting was 109 and the farmer-households planted slightly fewer fields at 95 which increased to 215 fields planted under supplemental irrigation.

As discussed above, the South Fields cover 3.5 km^2 and when supplemental irrigation is employed under the Rain-fed-SI scenario, the number of fields planted increases to approximately 200 fields covering an area of 180,000 m^2. If farmer-households utilised supplemental irrigation and were planting new fields each year, the farmer-households could expand the field system to cover the entire South Fields in 19 years. These time scales for the expansion of the Engaruka field system show that the field system could have been expanded rapidly within the time in which Engaruka was occupied. However, these timescales do not take into consideration sediment accumulation rates which would further increase the time it would take to build fields to the sediment depths observed from archaeological excavations.

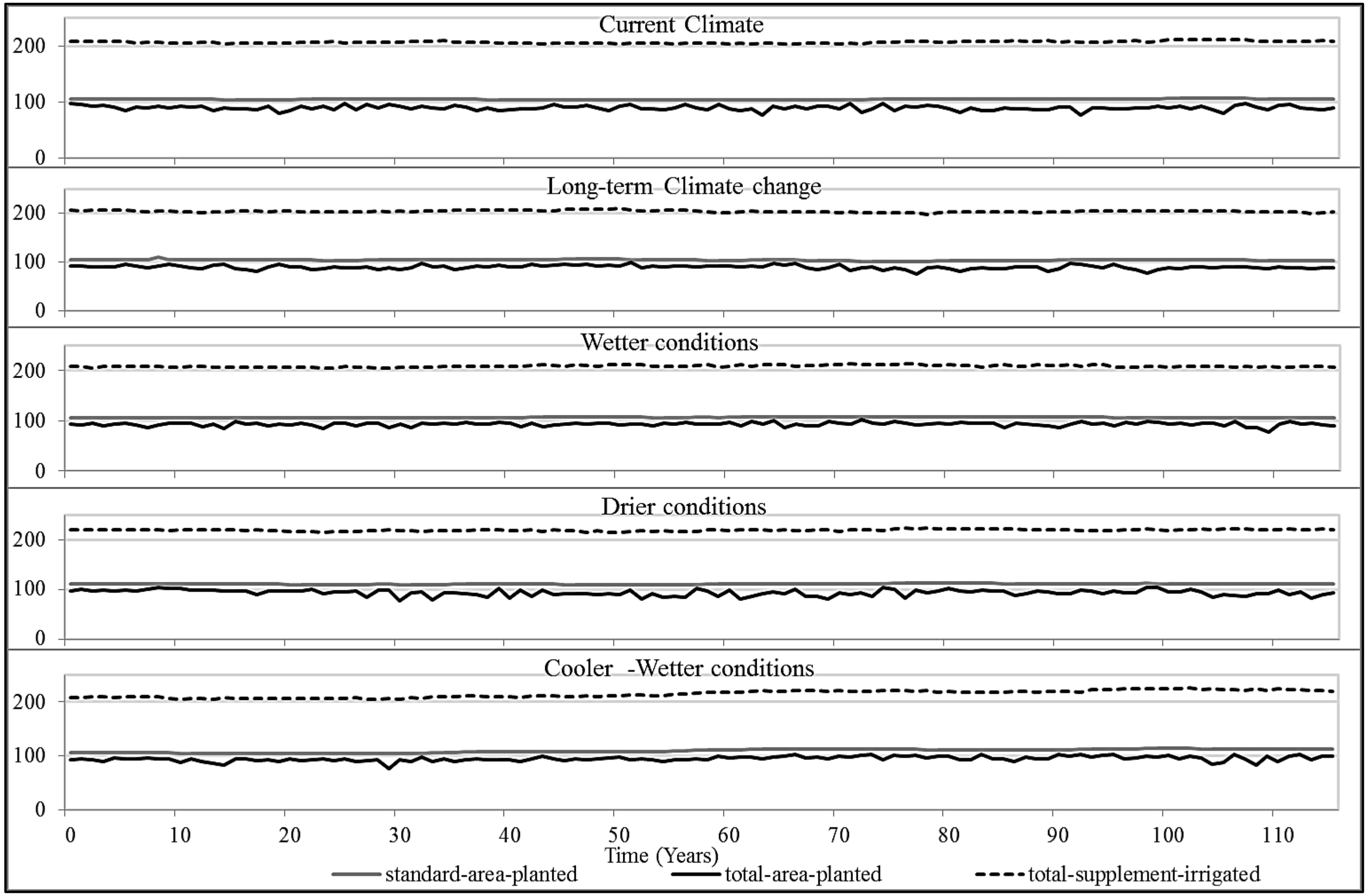

Figure 42: Total number of fields planted over time under Rain-fed-SI agriculture showing the standard area planted, the actual area planted by the farmer households and the total area under supplemental irrigation for climate scenarios (TM-01 to TM-05)

In the Rain-fed-SI scenario, the farmer-households would first increase the area planted in response to soil moisture stresses in order to try and maintain productivity and would incorporate supplemental irrigation when needed. This would result in much lower energy costs as the infrastructure used for irrigation might not need to be maintained as often as it would be in the Irrigated scenario. The combination of extensive and intensive practices under the Rain-fed-SI scenario provides a possible pattern for the development of the Engaruka system, whereby the reliance on rain-fed agriculture resulted in expansion of the field system. Meanwhile the use of supplemental irrigation helped farmer-households maintain crop yields and productivity as well as leading to the development of the irrigation infrastructure while allowing the farmer households to benefit from irrigation and keeping the energy costs low.

5.4.2 Impact of climate variability and water availability

The results of the model simulations show that under different climatic conditions, the number of fields varied for the different scenarios of Rain-fed-SI and Irrigated agriculture (Figure 43 and Figure 44). Under TM-01 simulation for current climate the standard number of fields for Rain-fed-SI was 105 for 293 inhabitants while the total fields planted was 90 fields over the 155 years of the simulation. Meanwhile in the Irrigated scenario, the standard number of fields averaged 86 for 235 inhabitants and the actual area irrigated was 47 fields. Under TM-02 simulation for long-term climate variability, the standard area planted under the Rain-fed-SI scenario was 104 fields for 286 inhabitants but the total area actually planted was 90 fields. While in the Irrigated scenario the standard number of fields was 99 for 273 inhabitants but the actual total area irrigated was 53 fields (Figure 43). The number of inhabitants affects the standard area that the farmer-households could plant, so as the total inhabitants increase or decrease, the standard area planted varies as well. This is best illustrated in the TM-01 simulation under the Irrigated agriculture scenario in which the standard area decreased when the number of inhabitants decreased in the time period Year 10-20. This decrease was due to some farmer-households being unable to adequately meet energy needs from the yields obtained and died out.

Results of the TM-01 and TM-02 simulations show that under both Rain-fed-SI and Irrigated scenarios, farmer-households planted fewer fields than the standard area and were still able to meet their energy needs (Figure 43 and Figure 44). The standard number of fields for Rain-fed-SI and Irrigated scenarios stayed constant under both TM-01 and TM-02 climate simulations but the actual area planted fluctuated from year to year due to farmer responses to seasonal variability in soil moisture. The farmers responded by either increasing the area planted or irrigating their fields or having no response that would result in loss of crop biomass. Under TM-01 in the Rain-fed-SI scenario the fluctuations in the number of fields planted from year to year were slight when compared to the average of 90 fields, where in some instances the lowest number of fields planted was 76 fields while the highest number of fields was 98. In contrast, under TM-01 in the Irrigated scenario, the fluctuations were greater as compared to the average of 47 fields, with farmer-households increasing the total area of irrigated fields to almost double the mean at 73 fields, while the lowest number of fields irrigated was 31 fields. In addition, despite a drop in the number of inhabitants in the system in Year 15- 20, the total area irrigated did not decrease immediately. This could be due to other farmer-households also taking advantage of this loss of inhabitants to increase their own fields in response to soil moisture stresses.

The fluctuations in fields planted from year to year were more noticeable for both Rain-fed-SI and Irrigated under simulations for TM-02 where the effects of long term climate events such as prolonged dry periods and wetter periods were incorporated (Figure 43). Under Rain-fed-SI the fluctuations were similar to those under current climate conditions, with increases of up to 98 fields as compared to the average of 90 fields, and lower than average area planted at 76 fields. For the Irrigated scenario, fluctuations in the total area irrigated were more noticeable and more frequently occurring as compared to simulations in TM-01. Under TM-02, the total area irrigated increased to 85 fields as compared to the average of 53 fields and went as low as 31 fields.

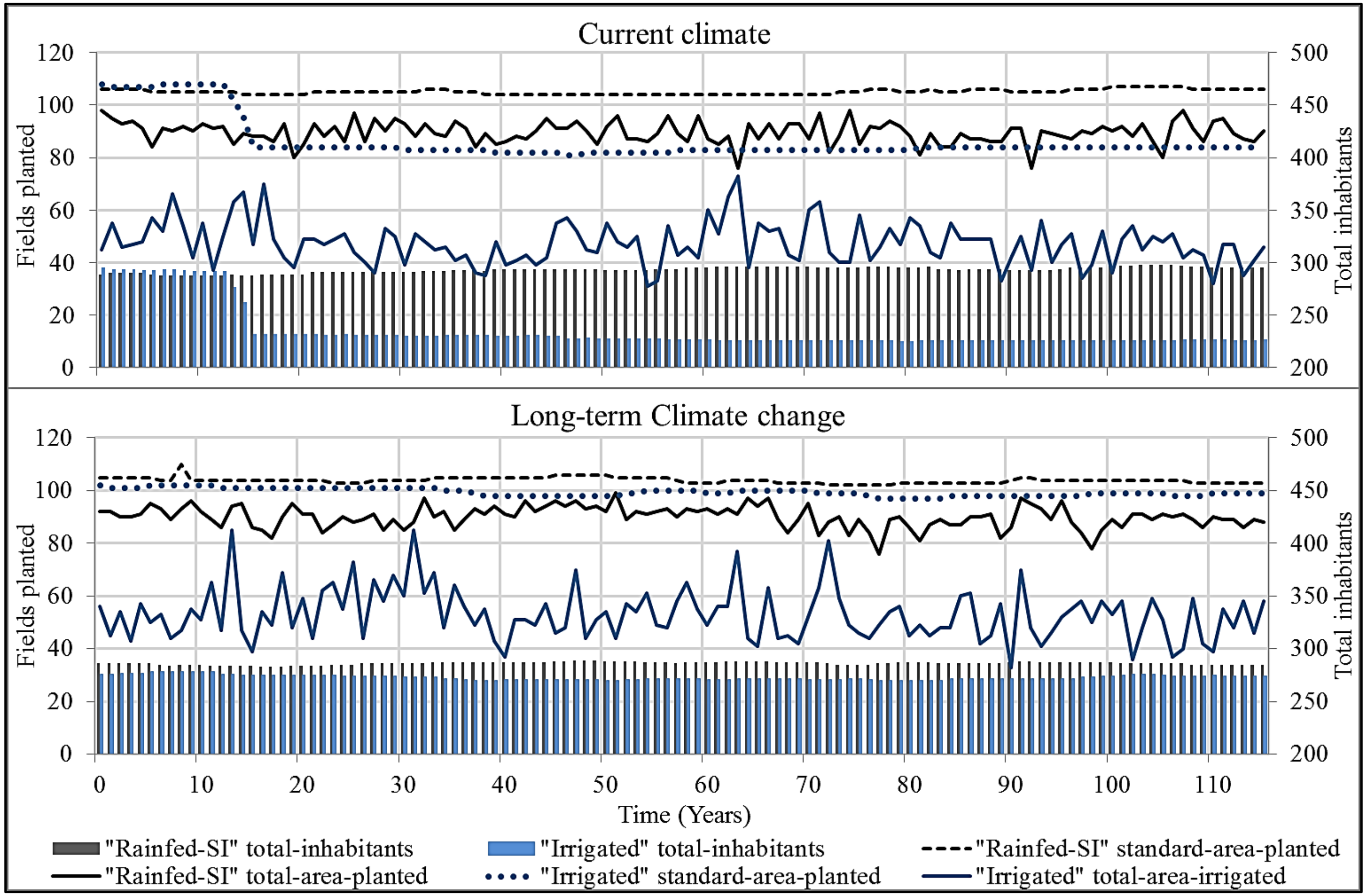

Figure 43: Total number of fields planted over time under Rain-fed-SI and Irrigated scenarios agriculture showing the standard area planted and the actual area planted by the farmer households under climate scenarios for current

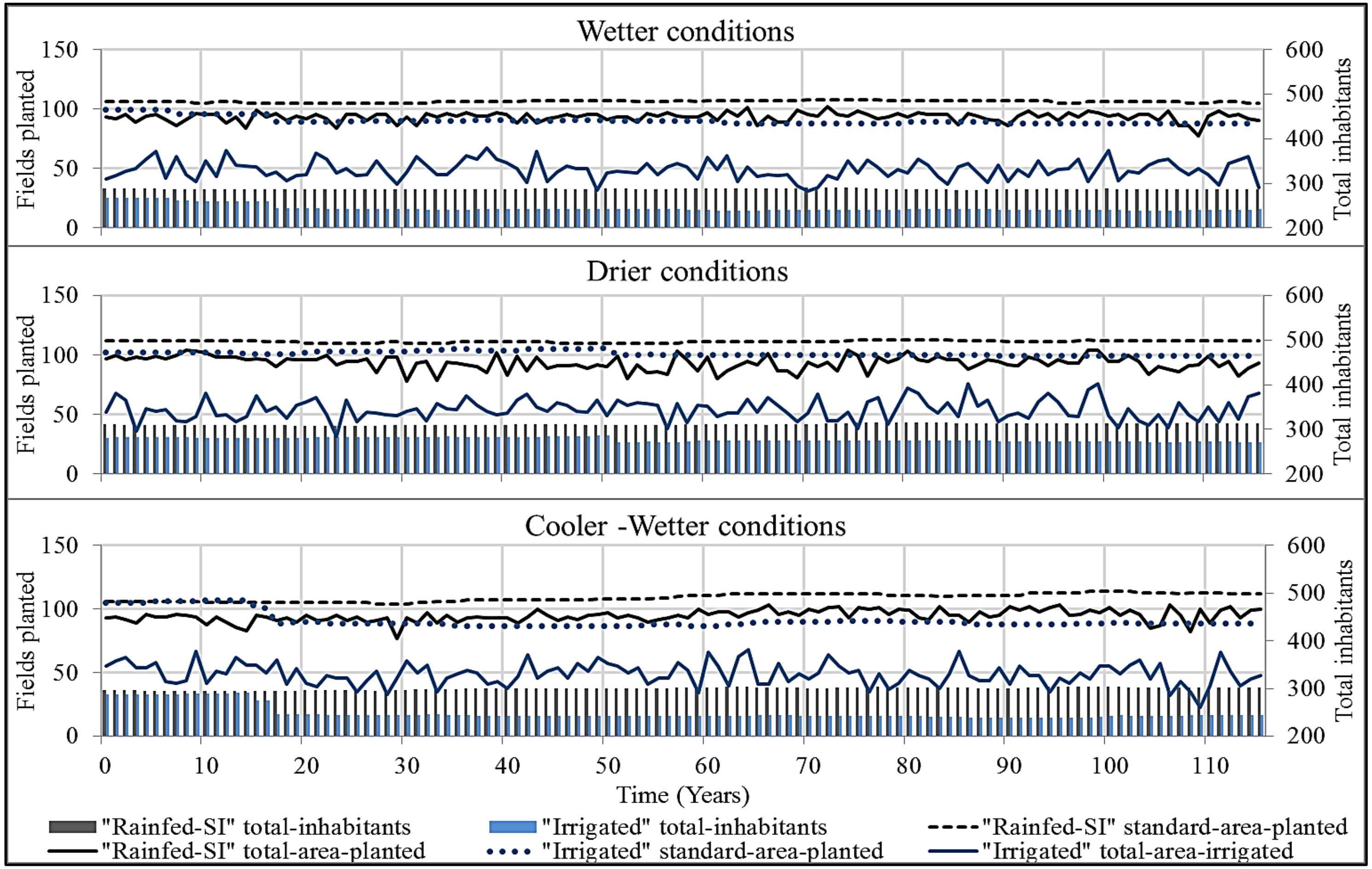

Figure 44: Total number of fields planted over time under Rain-fed-SI and Irrigated scenarios showing standard area planted and actual area planted by the farmer households under climate scenarios for wetter conditions (TM-03), drier conditions (TM-04) and cooler-wetter conditions (TM-05)

The frequency in contraction and expansion of fields for the Irrigated scenario as compared to the Rain-fed-SI in the simulations for TM-02 point to the effect long-term climate variability in combination with seasonal variability would have on the field system under these two scenarios. The increased frequency of field expansion under irrigation would place additional pressure on farmer-households in terms of the energy costs involved in constructing and maintaining fields. This can be seen further when exploring TM-04 below that explores the effect of prolonged dry conditions on the responses of the farmer-households (Figure 44).

Results of the simulations of TM-03 for wetter conditions show that for Rain-fed-SI, the standard area was an average 106 fields for 287 inhabitants but the total area planted was 93 fields. While for the Irrigated scenario, the standard field number was 90 fields for 244 inhabitants but the total area irrigated averaged 49 fields (Figure 44). In TM-04 simulating for drier conditions, for Rain-fed-SI, the standard area was an average 111 fields for 311 inhabitants but the total area planted was 93 fields. While for the Irrigated scenario, the standard field number was 101 fields for 277 inhabitants but the total area irrigated averaged 54 fields. In TM-05 the simulation for cooler and wetter conditions, under Rain-fed-SI, the standard area was an average 109 fields for 300 inhabitants but the total area planted was 95 fields. While for the Irrigated scenario, the standard field number was 91 fields for 249 inhabitants but the total area irrigated averaged 49 fields.

The year to year fluctuations can also be seen when exploring the effects of prolonged extremes in climatic conditions (Figure 44). Under simulations for TM-03 under the Rain-fed-SI scenario the total area planted increased to 102 fields and went as low as 77 fields while under the Irrigated scenario the total area irrigated increased to a high of 67 fields and as low of 31 fields. In TM-04, the total area planted under Rain-fed-SI increased to 104 fields and decreased to 78 fields while under the Irrigated scenario the total area irrigated was expanded to 76 fields and contracted to as few as 32 fields. In TM-05, under the Rain-fed-SI scenario the total area planted varied from highs of 103 fields to as low as 77 fields, while under the Irrigated scenario the total area irrigated rose as high as 68 fields and dropped to lows of 23 fields.

5.4.3 Impact of alternative activities

Results of the simulations on the impact of alternative activities (TM-06) show that when provided with alternative subsistence activities that provide yields greater than farming, farmer households would be attracted away from farming (Figure 45 and Figure 46). The results of the TM-06 simulations show that the farmer-households under the Rain-fed-SI scenarios were attracted to the alternatives subsistence activities faster than the farmers under the Irrigated scenarios for the different climatic conditions simulated. This could be because the yields obtained under Irrigated were higher than Rain-fed-SI and thus when the farmers compared their yields to the ideal yields there would have been a higher incentive for those under Rain-fed-SI as compared to Irrigated. The farmer-households compare their yields to ideal yields every year and assign a positive or negative score based on whether their yields were less or greater than the ideal yields. When the farmer-households achieve a positive score greater than the minimum viable alternatives threshold (in this case 12 instances making a cumulative score of one year) in which their actual yields are less than the ideal yields, the farmer-households make the decision to switch to the alternative subsistence activities.

Results of the simulations show that under current climate conditions (TM-01), the farmers begin switching to alternative subsistence activities at Year 26 while in the Irrigated scenario they begin at Year 30 (Figure 45). In addition, in the Rain-fed-SI scenario the switch to alternative activities is more gradual, taking up to Year 78 for the last household to switch over, a period of 53 years. In contrast, under the Irrigated scenario the farmers' shift to alternative activities is more abrupt with all farmer households switching over within a seven year period between Year 30 and Year 36. When simulated under the Long-term climate change (TM-02) scenario, the shift from farming to alternatives activities is even more abrupt for both Rain-fed-SI and Irrigated scenarios. Under Rain-fed-SI the farmers take less than 20 years to switch completely from farming between Year 26 to Year 45, while under the Irrigated scenario the farmers take five years to switch between Year 30 and Year 34 (Figure 45). The shorter time taken to switch from farming to alternative subsistence activities under TM-02 can be attributed to the effect of prolonged droughts that occur between Year 30- 49. These prolonged dry periods result in low yields from agricultural production and thus the farmer-households might be attracted to alternative subsistence activities that provide better yields. This could be due to the mobility of alternative subsistence activities such as pastoralism, where the farmers who switch to pastoralism can then leave the region and move to other places in the landscape that allow them to produce better yields.

In simulations for wetter conditions (TM-03), the farmers' shift from farming occurs sooner in the Rain-fed-SI scenario, starting in Year 20 and taking six years for all the households to switch over by Year 25. Farmer-households under the Irrigated scenario take slightly longer to begin switching over to the alternatives but take a similar amount of time to complete the change from Year 22-27 (Figure 46). While it would be easier to continue farming in wetter conditions, the increased rainfall availability could also affects the alternative subsistence activities, resulting in these yields being as, or more, than those obtained from agriculture. This is in the case where the farmers base their decisions only on maximising their yields; but as discussed in the sections below, social norms can encourage the farmers to prioritise agriculture over the alternatives.

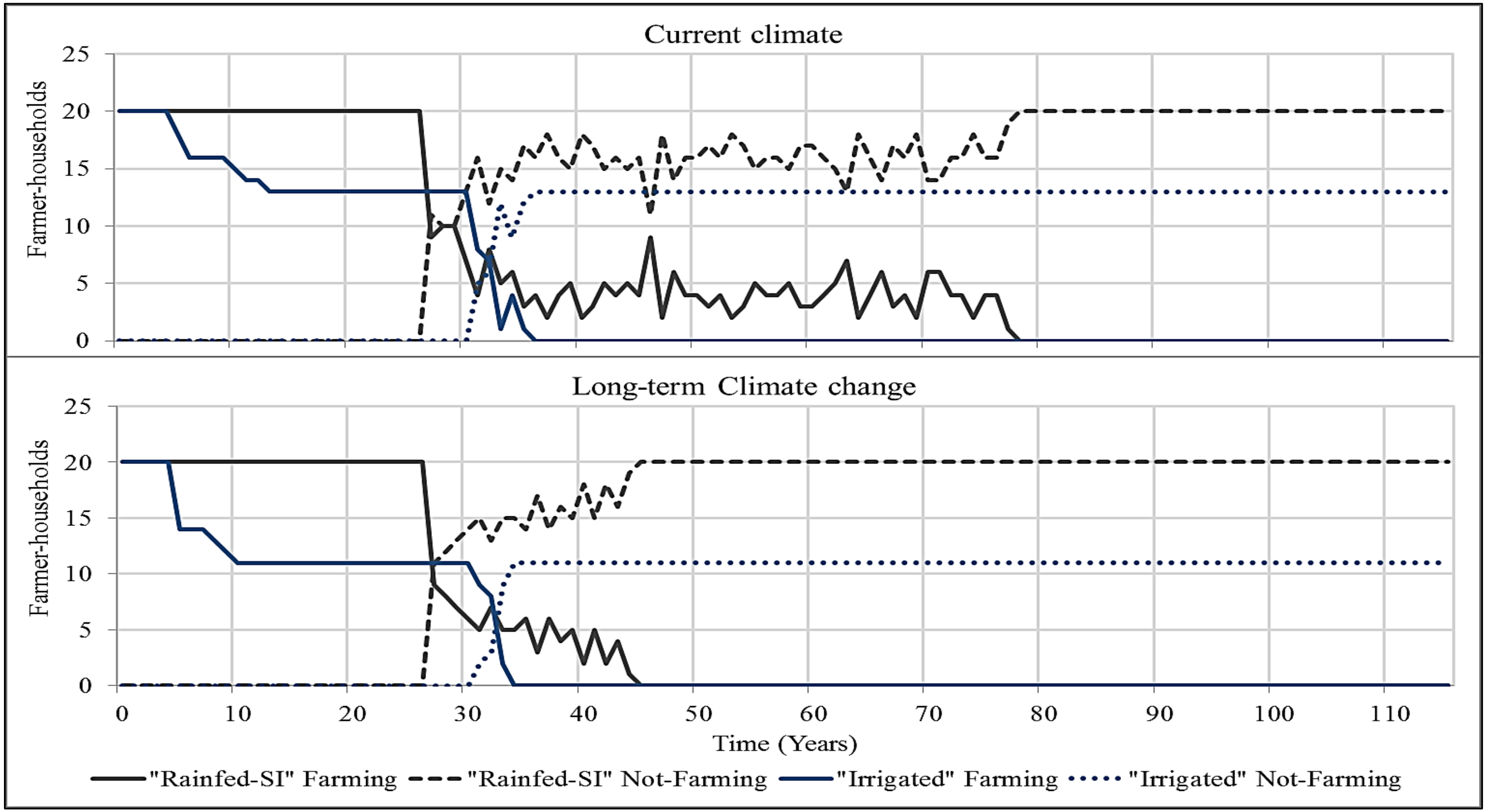

Figure 45: Effect of alternative activities scenarios (TM-06) on the number of farmer households in the Rain-fed-SI and Irrigated scenarios engaging in farming or switching to alternative subsistence activities over time under scenarios of current climate (TM-01) and Long-term climate change (TM-02)

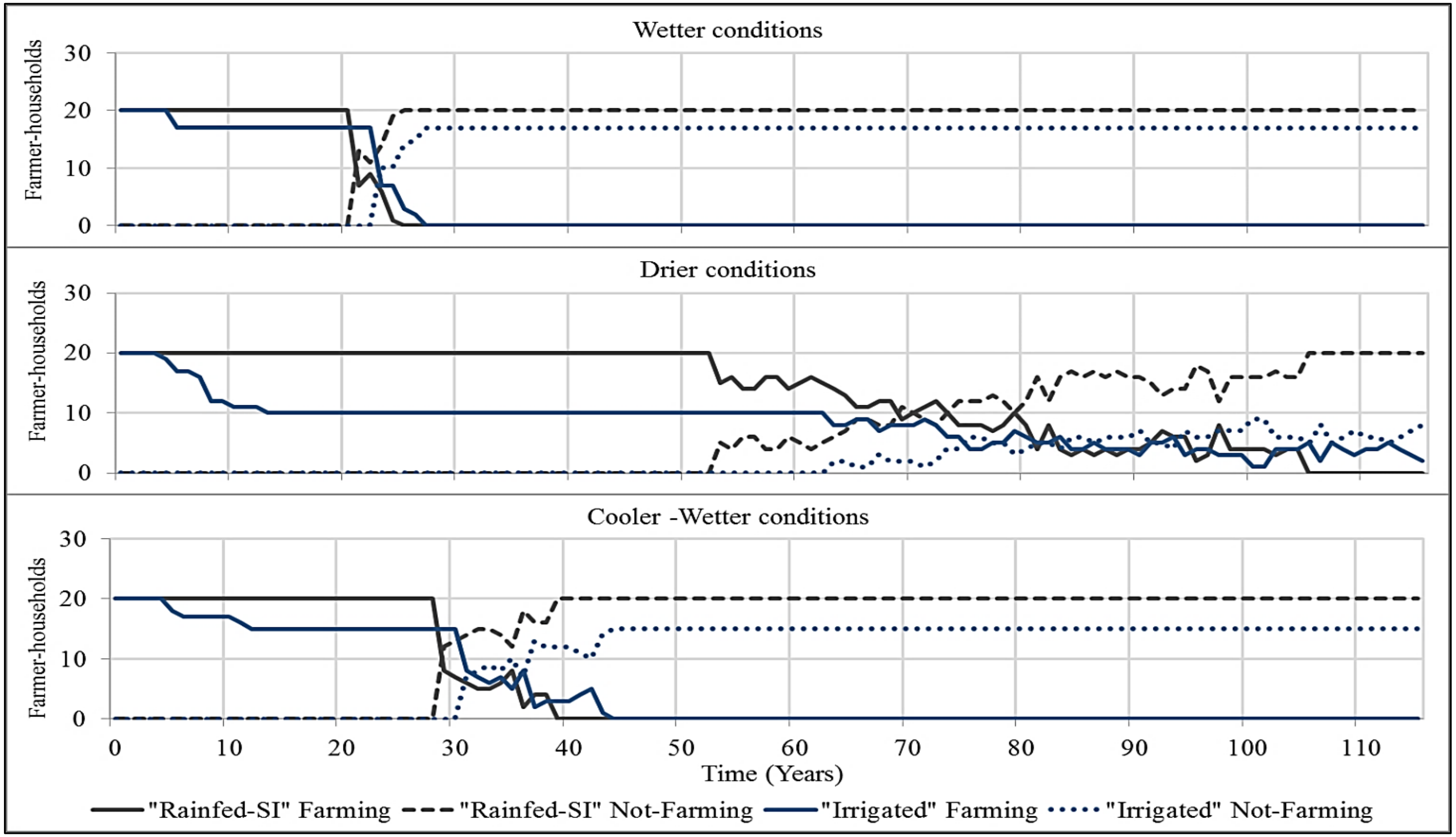

Figure 46: Effect of alternative activities scenarios (TM-06) on the number of farmer households in the Rain-fed-SI and Irrigated scenarios engaging in farming or switching to alternative subsistence activities over time under scenarios of wetter conditions (TM-03), drier conditions (TM-04) and cooler-wetter conditions (TM-05)

Simulations for TM-06 under drier conditions (TM-04) saw farmer-households staying longest under farming and taking the longest time to transition from farming to the alternative activities. Under Rain-fed-SI farmers begun to switch from farming to alternative activities in Year 52 and took up to Year 105, a total of 54 years for all the farmers to shift away from farming. In the Irrigated scenario, farmers begun switching in Year 62 and by the end of the simulation at Year 115 the farmers-households had not all switched over with 2 households still continuing to farm (Figure 46). Simulations for TM-06 under cooler-wetter conditions (TM-05) showed that farmer-households begun to switch from farming in the Rain-fed-SI in Year 28 and took 12 years for all the farmers to switch by Year 39. While under the Irrigated scenario, farmer-households began switching to alternative activities in Year 30, taking 15 years for all the farmers to have switched by Year 44.

The drier conditions simulated in TM-04 can be contrasted with the prolonged droughts simulated in TM-02 (Figure 45 and Figure 46). Under TM-02 the farmers were subjected to droughts after periods of relatively good climate conditions, these changes would not have necessarily affected all activities in the landscapes equally and there could have been lag on the effect to alternatives or the alternatives were unaffected. In such cases the farmers would have been able to contrast the better yields from previous harvests to the yields during the prolonged droughts as well as to the alternatives unaffected by the droughts. This would have influenced their perception of the viability of the alternatives and encouraged a faster shift away from farming. In contrast, the drier conditions simulated in TM-04 presented the initial conditions that would have affected both the farming and alternatives such that farming ends up being more attractive to the farmers as compared to the alternatives. Once farmer-households switch to alternative activities, there is little social incentive to return to farming once conditions improve. The factors that would result in the farmers moving away from agriculture can combine with the climatic factors and include reduced interest in farming, socio-political collapse (Dixon *et al.* 2014; Hannaford *et al.* 2014; Westerberg *et al.* 2010; Benayas *et al.*) and can be part of the risk response of the community (Thomas *et al.* 2007). However, while attractive alternative subsistence activities can incentivise farmer-households to switch, social norms can influence the decision to switch over with individuals conforming to the more dominant or more accepted practices of the community.

5.4.4 Influence of Social norms and networks

Results of the simulations on the effect of social norms (TM-07) showed that these affected the incidence of farmer households switching from farming to alternative subsistence activities (Figure 47 and Figure 48). The social norms effect compared the effect of the probability of farmer-households continuing to farm or switching to alternatives. The model was simulated under TM-07 for 0.2 and 0.8 probabilities of the farmer-households continuing with farming. When simulated under current climate (TM-01) the farmer-households in the Rain-fed-SI scenario would completely switch to alternative subsistence activities under social norms effects of 0.2 while at 0.8 only a few farmers would switch to the alternatives while the majority would continue farming (Figure 47). When the social norms effect was low at 0.2, the farmer-households would begin switching in Year 26 and by Year 78 all the households employed alternative subsistence activities. In contrast when the social norms effect was at 0.8, the farmer-households would begin switching in Year 26 but majority of the farmers would be incentivised to continue or return to farming such that by Year 115 the majority of households, 16 farmer-households continued farming while 3 switched to the alternatives (Figure 47). In addition, while some farmers would switch from farming, the social norms effect incentivised them to return to farming eventually such that at the end of the simulation, 16 farmer-households were farming while 3 households had switched to alternative subsistence activities. This is in contrast to where there was little influence of social norms resulting in all 20 farmer-households switching to the alternatives.

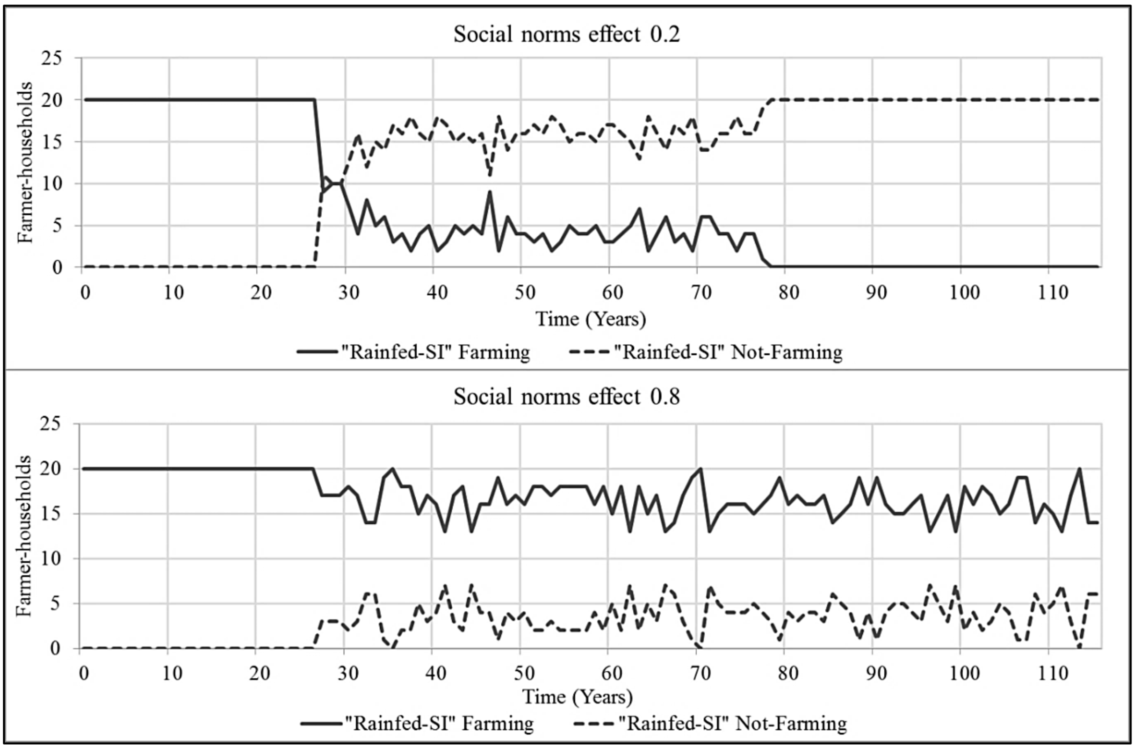

Figure 47: Effect of social norms (TM-07) on the number of farmer-households engaging in farming or switching to alternative subsistence activities over time in the Rain-fed-SI scenario and under current climate conditions (TM-01)

Simulations under TM-07 showed a similar effect on the Irrigated scenario under current climate (TM-01) where the strong influence of social norms at 0.8 resulted in 10 farmer-households continuing with farming and five switching to alternative activities (Figure 48). This is as compared to the limited social norms effect at 0.2, where all 11 of the remaining farmer-households switched to alternative subsistence activities. When the social norms effect was low at 0.2, the farmer-households would begin switching in Year 30 and by Year 34 all the households were employing alternative subsistence activities. In contrast when the social norms effect was at 0.8, the farmer-households would begin switching in Year 30 but majority of the farmers would be incentivised to continue or return to farming such that by Year 115 the majority of households, 10 farmer-households continued farming while five switched to the alternatives. In addition, farmer-households who had switched to the alternatives were also influenced to return to farming where the social norms effect was stronger, resulting in more farmers continuing with farming as compared to the farmer-households that switched to the alternatives.

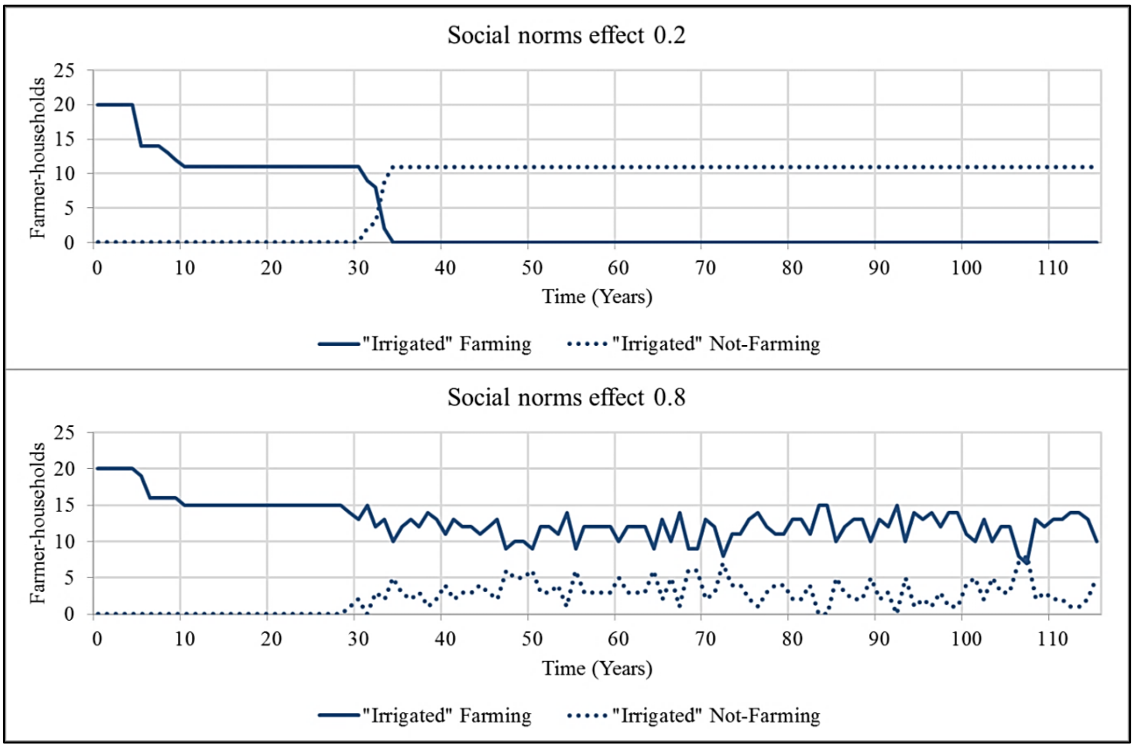

Figure 48: Effect of social norms (TM-07) on the number of farmer-households engaging in farming or switching to alternative subsistence activities over time in the Irrigated scenario and under current climate conditions (TM-01)

The influence of social norms on the farmer-households highlight that in conditions where farming might not have been as attractive as other alternatives, the households are incentivised to continue farming. Studies have found that the decisions made are not necessarily based purely on the idea of maximising yields and other factors play a role (Janssen and van Ittersum 2007). In addition, the farmers may have additional buffering strategies such as food stores and cooperative action such as risk pooling which have been studied in pastoralist communities such as the Maasai (Aktipis *et al.* 2011). In addition, cooperative and collective actions that support the management of the farming systems could influence the choice of the farmer-households on whether to continue farming or to switch to alternative subsistence activities. Where the farmers are engaging in cooperative activities that require close networks, the interconnected nature of interactions might in turn influence the farmers' choices as compared to if the households were independent of each other. The collective action of the farming households may also support their decisions as the farmer households can share information and influence each other's decisions (van Duinen *et al.* 2016, 340). The effect of social norms could have been one of the reasons for the continued use of the Engaruka system with the farmer-households incentivised to continue farming as opposed to pursuing alternative subsistence activities even given unfavourable climatic conditions.

5.4.5 Impact of population

The results of the TM-08 simulations for the effect of population size on the farmers choice of farming or not farming show that even when there is little influence from social norms, the farming system continues to be utilised for longer when there are more households than when there are fewer households (Figure 49). This could be partly due to the larger number resulting in the process of switching taking longer, and it could also be due to the effect of social cohesion that could mean that even with a low social norms effect, the farmers could still be influenced by their neighbours to continue with farming. In addition, the presence of more farmer-households engaging in farming could influence the choice of farmers who had switched to alternatives to switch back to farming. Results of the TM-08 simulations under current climate conditions (TM-01) show that under Rain-fed-SI scenario, more farmer-households continued farming when the farmer-households numbered 50 (Figure 49, 1b) as compared to when there were 20 households (Figure 49, 1a). When there were 20 farmer-households, the switch to alternative activities begun in Year 26 with all the farmers switching by Year 78, taking 53 years (Figure 49, 1a). In contrast, when there were 50 farmer-households, the switch to alternatives begun at a similar time (i.e. Year 26) but by the end of the simulation in Year 115 there were still 15 farmer-households engaging in farming (Figure 49,1b).

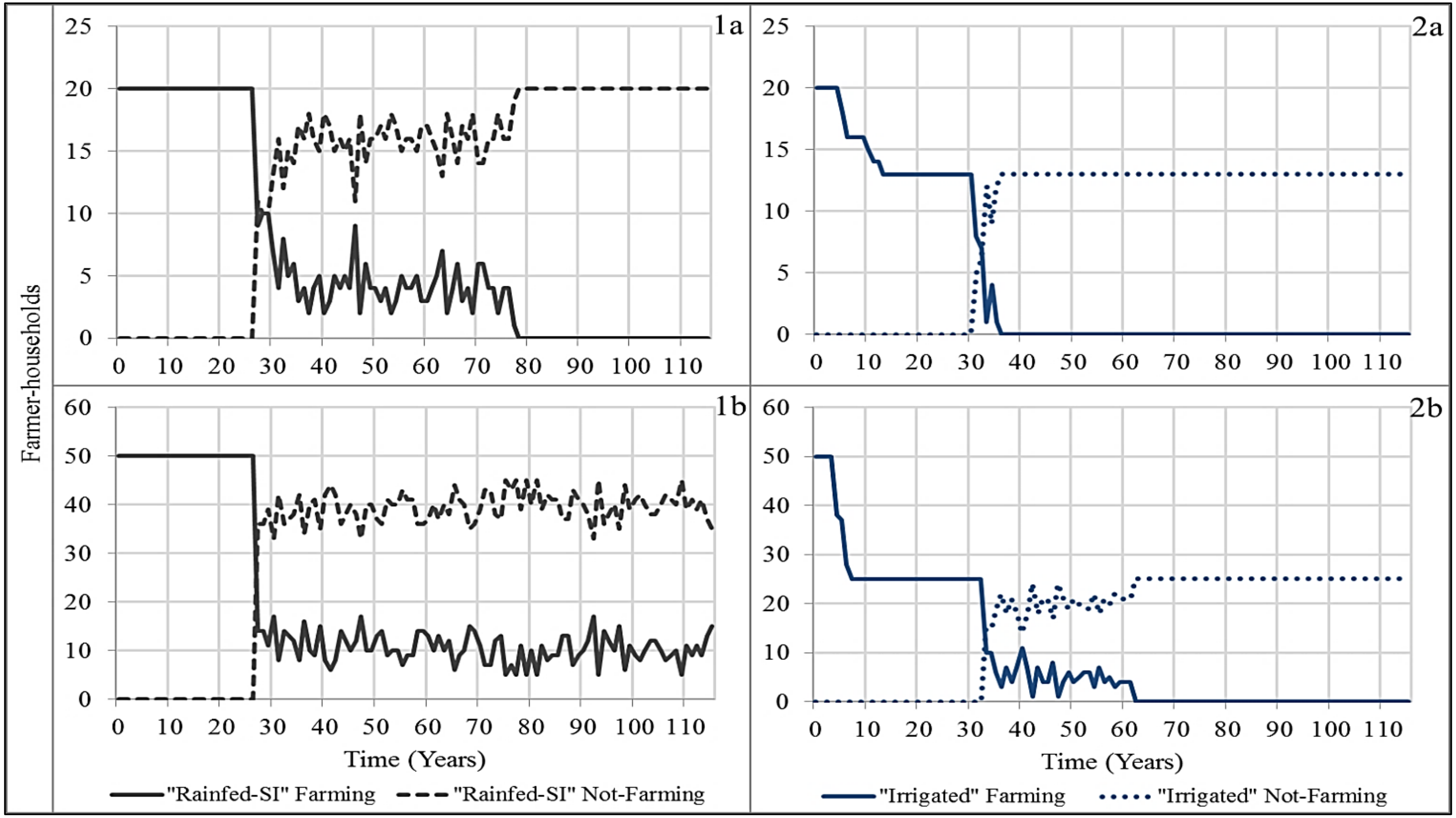

Figure 49: Effect of population size on the number of farmer-households engaging in farming or switching to alternatives over time under Rain-fed-SI (1a, 1b) and Irrigated (2a,2b) scenarios given current climate conditions (TM-01)

Under the TM-08 simulations, the farmer-households also take a longer time to switch to the alternative activities under the Irrigated scenario when comparing simulations with 20 versus 50 farmer-households (Figure 49, 2a, 2b). Results of the simulations show that under the Irrigated scenario when there were 20 farmer-households the farmers all switched from farming to alternative subsistence activities between Year 30 and Year 36 (Figure 49, 2a). This is in contrast to the when there were 50 farmer-households where the switch began slightly later at Year 32 and took 31 years for all the households to switch to alternative subsistence activities by Year 62 (Figure 49, 2b). In the TM-08 simulations, the increased population size has a positive effect on the continued use of the system such that even as some farmer-households switch to alternative subsistence activities there are enough farmers left that continue utilising the farming system. In addition, the effect of population size can also act as a social norm such that where the majority are pursuing an action this incentivises others to also pursue a similar action.

5.5 Role of Climate, Alternative activities, Social norms and Population on the expansion and use of the Engaruka System

The scenarios explored in the model present important steps in understanding the interaction of environmental and socioeconomic factors that influenced the expansion and continued use of the Engaruka system. The simulations incorporating Rain-fed-SI and Irrigated scenarios point to the influence of different agricultural practices had on crop productivity and yields under different climatic conditions. In addition, by simulating the Rain-fed-SI and Irrigated scenarios, the energy costs and benefits of the different agricultural practices can be assessed to support interpretations of the factors that influenced the farmers' choices in the construction and development of the Engaruka system. Understanding the effect of the different climate conditions simulated in the model point to the influence the different climate scenarios have on the development and expansion of the fields system. These simulations would help support interpretations of the archaeological data by providing further information on how the climatic conditions affect the area that farmers can feasibly farm and the timelines involved in the expansion of the fields given the different agricultural strategies of Rain-fed-

SI and Irrigated. The simulation of scenarios incorporating alternative activities, social norms, and population, point to factors that influenced the continued use of the system as well as possible reasons for its abandonment. Combining the simulation of these scenarios with climatic scenarios supports understanding of the interaction of factors that would have influenced the construction expansion and continued use of the system over time. Interpretations of these model results would further support assessments of the sustainability of the Engaruka system over time.

The results of the model simulations for the Irrigated and Rain-fed-SI scenarios show that the Irrigated scenario resulted in higher yields for the area planted with yields of 13, 000kg ha^{-1} with farmers constructing 50 fields as compared to the Rain-fed-SI results of 10,000 kg ha^{-1} where farmers built 90 fields. The higher yields from fewer fields highlights one of the reasons for the development of the Engaruka system, where the farmers improved their yields without increasing the area under cultivation; which is cited as one of the benefits of the use of irrigation (Wallace 2000). However, while the farmers achieved higher yields the Irrigated scenario resulted in higher energy costs at 2,200 MJ a^{-1} as compared to the Rain-fed-SI at 1,500 MJ a^{-1}. These higher energy costs may increase the risks faced by the farmer-households such that if they utilise irrigation and fail to achieve the higher yields expected they may be at greater risk of collapse. The use of supplemental irrigation in the Rain-fed-SI scenario on the other hand would allow the farmer-households to maintain crop productivity with much lower energy expenditure. While the use of irrigation can mitigate against the effects of variability in soil moisture due to seasonal and long-term climate variability, the use of these fully irrigated systems can eventually lock the farmer-households into a rigid system with limited room for adaptation. This could point to one of the factors that led to the abandonment of the system as discussed further below.

Simulations for the different climate scenarios (TM-01 – TM-05) highlight the influence of climate and its effects on soil moisture on the area planted by the farmer-households under the Rain-fed-SI and Irrigated scenarios. The farmer-households planted fewer fields than the standard number expected for the given number of inhabitants and were still able to meet energy needs for the households.

When averaged across the different climate scenarios, the farmer-households under the Rain-fed scenario required a standard area of 107 fields for 295 individuals but only planted 92 fields, while in the Irrigated scenario the standard areas was 93 fields for 256 individuals but only irrigated 50 fields. The farmer-households averaged 50 fields a year under the Irrigated scenario and 90 fields under the Rain-fed-SI scenario. This increased to 200 fields when supplemental irrigation was employed to both the total area planted, and any additional fields planted when trying to deal with soil moisture stresses. Given that each field cover an area of 900 m^2 the farmer-households were cultivating between 45,000 to 81,000 m^2 each year and as high as 180,000 m^2.

As outlined in the sections above, the model outputs on the total area planted can provide information on the patterns of expansion of the field system and the timescales that could be involved. Given the archaeological extent of the South Fields at 3.5 km^2 (Stump 2006b, 156) the model results can be used to interpret the timelines involved in the expansion of the field system. The estimates of the area of the fields constructed show that it would take as short as 19 years and between 43 to 77 years to build the field system to cover the entire South Fields, if the farmers are planting new fields every year. In addition, the model results show that given the year to year fluctuations under different climate simulations, the number of fields planted can also vary greatly ranging from as few as 23 fields to as many as 98 fields in a year. These yearly fluctuations in the fields planted further expands our interpretations of the timelines involved in the development and expansion of the field system such that if farmer households construct 23 fields covering 20,700 m^2 at a time, it would take approximately 169 years to construct the South Fields, while if constructing 98 fields covering 88,200 m^2, it would take 39 years to expand the field system over the entire South Fields. The rates for the construction and expansion of the field system to cover the South Fields therefore range from 19 years to 169 years. However, these values provide only minimum rates for the expansion of the system and do not incorporate factors such as the time it would take to accumulate soils in the sediment trap fields as discussed in Chapter Four. These results point to the gradual expansion of the system with action iterated over time by a small numbers of farmer households resulting in a complex system (Bevan and Conolly 2011, 1313) rather than through a single event of large-scale expansion.

These model results show that field construction under Rain-fed-SI and Irrigated scenarios and the annual variations in fields planted mean that the entire system does not have to be in continuous use at all times. Interpretations put forward on other agricultural systems by Davies (2014) argue that despite the evidence of a complex agricultural system, the communities utilising them do not necessarily utilise the entire field system. In addition, the farmer-households could have constructed the field system utilising agricultural practices in the Rain-fed-SI scenario such that they can build fields and expand them further under supplemental irrigation. The farmers can then reduce the area under cultivation where the conditions suffice for adequate crop yields. The farmer-households can expand their field system and put in place and maintain the necessary irrigation infrastructure but engage in long fallow shifting farming similar to systems in Marakwet, Kenya (Davies *et al.* 2014) and Konso, Ethiopia (Ferro-Vázquez *et al.* 2017). The expansion and contraction of fields in use annually can also be due to the available labour and water resources and related to the responses of the farmer-households as outlined in Chapter Two. Findings from interviews and focus groups showed that the farmers would focus their efforts on the fields that they expected to provide adequate yields and leave the other fields to fallow until needed (see Chapter Two). In this way the field system could have incorporated extensive practices through the expansion of the field system while simultaneously households could also engage in intensive agriculture either through use of supplemental irrigation or a fully irrigated system on the fields in use.

Simulations for the alternative activities show that the farmer-households left the Engaruka system where viable alternative subsistence activities were available. Where farmers' yields were lower when compared to those from alternative activities, the households would make the choice to switch. The farmer-households under Rain-fed-SI would leave the system much faster than those under the Irrigated scenario. This relates to the yields obtained under the Irrigated scenario which were higher than those under the Rain-fed-SI. The attractiveness of alternative activities points to one of the possible reasons for the abandonment of the Engaruka system, such that households would eventually be drawn away from farming and result in the abandonment of the system (Westerberg *et al.* 2010). There is thus no reason to see abandonment as evidence of a catastrophic economic or environmental collapse. Climate also affected the farmers' decision to switch to alternatives. The model results showed that under wetter conditions farmer households would switch to the alternatives much sooner than during drier conditions for both Rain-fed-SI and Irrigated scenarios. This could be because as conditions improve for farming, they could also be improving for the alternative subsistence activities; thus where the farmers are purely driven to maximise yields, they would switch when the alternatives provide better yields. As conditions became drier, farmer–households would continue farming for longer before switching to alternatives, and under the Irrigated scenario not all the households left the farming system. While farmers under Rain-fed-SI made the switch sooner, the farmers took long periods of time to complete the transition to alternatives. In contrast, the farmer-households under Irrigated would transition much faster. This could be due to the effect of the increased vulnerability under irrigation that would result in the farmers suffering higher losses and this would then make the alternative activities more attractive.

However, the role of social norms and population size in the model would further affect the continued use of the system. The effect of social norms resulted in more farmer-households continuing to farm under both Rain-fed-SI and Irrigated scenarios despite the viable alternative subsistence activities available. This could point to another factor for the continued use of the Engaruka system whereby farmers are incentivised to farming for factors other than to maximise yields, and would also be influenced by the actions of their neighbours (van Duinen *et al.* 2016, 340; Janssen and van Ittersum 2007). In addition, having a larger population plays a role in the continued use of the system where having more households meant that, even as some farmers left the system for alternative subsistence activities, there remained a sufficient number of households who continued to utilise the system. In this way social norms and population play a role in the continued use of the system.

5.6 Conclusions

The TIME-MACHINE model provides first steps in understanding the factors that influenced the development and expansion of the Engaruka water-management system, its continued use and sustainability, and its eventual abandonment. The model shows how the interplay of environmental and social factors could have influenced the development and expansion as well as abandonment of the system. The Engaruka system could have developed under the Rain-fed-SI scenario where the farmers employ expansive agricultural practices with intensive practices of supplemental irrigation. Through the use of supplemental irrigation, the farmer–households would have been able to combine expansive and intensive practices showing that intensification does not need to follow a linear path from the development of extensive to intensive agriculture (Erickson 2006). This is particularly relevant in maintaining the sustainability of the system as climate change could negatively affect crop productivity but utilising this technique could allow the system to remain productive through the use of supplemental irrigation while requiring lower energy costs than a fully irrigated system.

The model results support archaeological interpretations that the field system was built gradually over time by a small number of households resulting in the complex system. The farmer-households could utilise Rain-fed with supplemental irrigation and when climate conditions became unfavourable could utilise supplemental irrigation. In some cases when faced with drier climate, the farmer-households could have transitioned into a fully irrigated system which would allow them to continue utilising the system for longer. In combination with the effect of social norms, the farmers would have been incentivised to continue farming instead of switching to alternative subsistence activities. In addition, an increase in the number of households would extend the use of the field system such that as some households leave to pursue alternative subsistence activities, there is a sufficient population left behind that continues to utilise the system. However, if over time the farmer-households became locked in a rigid irrigated system they would have been more vulnerable to environmental or social stresses. One such stress could have been the loss of the water resources that fed the irrigation system. Archaeological studies of the Engaruka site by Sutton (1998) show that the complex irrigation system relied on water resources from five major rivers however, currently only one of the rivers remains perennial i.e. the Engaruka River. As the water resources reduced, productivity would have reduced negatively affecting yields. The alternative activities could have then become more attractive and resulted in farmer-households leaving the system to pursue these alternatives. Given the lack of archaeological evidence of system degradation through agricultural mismanagement (Westerberg *et al.* 2010; Stump 2010a), the model results point towards gradual abandonment when water resources for irrigation could no longer sustain the population.

The TIME-MACHINE model therefore enables interpretation of the factors that would have influenced the development of the Engaruka system and reasons for its abandonment. The model results support archaeological interpretations for the reasons for the abandonment of the Engaruka water-management system by demonstrating that the system could be built gradually by a small number of households, that the system development was influenced by a combination of environmental and social factors that influenced its continued use as well as facilitating its eventual abandonment. The model results support archaeological interpretations where supporting information is unavailable, making this model particularly relevant to similar studies on historical water-management. The model scenarios would be of particular interest in understanding how similar systems would have developed given the interaction of environmental and social factors.

Chapter 6 Synthesis and Conclusion

6.1 Overview

This chapter outlines a summary of the research conducted, and a synthesis of the aim of the research and the research questions addressed by the study. The model conceptualisation and the development of the agent-based models is summarised along with the main findings from the ABMs developed. The gaps in the research are presented and avenues for future expansion of the work are discussed. The recommendations that can be drawn from this research are discussed, together with avenues for future research and impacts for contemporary development agendas.

6.2 Synthesis

The research conducted explored the dynamics of the historical Engaruka water-management system that influenced its development and continued use from the 15th to 18th centuries CE. A wide range of interacting environmental and human factors influenced the development of the historical Engaruka system. These ranged from the environmental factors of climate and variability in water availability to human factors of labour, population size and decision-making on choices of agricultural practices. The aim of the research therefore was:

- To model the primary human and environmental factors and their interactions that influenced the development of the historical Engaruka water-management system in east Africa, over a temporal and spatial scale.

To achieve this overarching aim, the research utilised archaeological evidence, agent-based modelling techniques, analysis of hydrodynamics, DEM data and palaeoclimatic data analysis. The development of agent-based models that incorporate archaeological evidence, hydrological data, topographical data, qualitative data and palaeoecological data was put forward as a viable technique for the creation of a simplified reconstruction of the Engaruka system to answer three questions:

4. To what extent does the incorporation of irrigation canals and sediment trap fields influence the hydrologic and sedimentary processes across the landscape and the irrigation system over time?

5. To what extent does the modification of water movement influence crop production and crop yields within the system?
6. To what extent does the interaction of environmental and social factors influence the development and continued use of the Engaruka field system?

The agent-based models developed to answer these three questions incorporated data from palaeoenvironmental proxies, archaeological evidence as well as from fieldwork conducted in Engaruka and Konso. The data collection incorporated a variety of methodologies such as archaeological excavations, topographic surveys and GIS mapping of the study sites, hydrologic surveys, aerial surveys and semi-structured interviews and focus groups (Chapter Two). The archaeological excavations conducted in 2014 found that the field system in the south fields were constructed through sediment capture, with distinct similarities in how the sediment trap fields developed in the South fields and the North (Lang and Stump 2017). The topographic surveys mapped out the extent of agricultural fields and the evidence of archaeological features such as embankment walls. The data from these excavations was used to measure the depth of sediments captured in the fields, and together with the area of the study site, were used to estimate the volume of sediments captured. The results of the aerial surveys provided additional information on the pattern of field construction and the placement of irrigation canals relative to the sediment trap fields. The results of the hydrological surveys along the Engaruka River, Olemelepo River and adjacent off-take canals found that water velocities within these channels ranged between 0.2 – 1.0 m s^{-1} and the total suspended sediment transported ranged from 100 -800 mg L^{-1}. The flow rates within the channels and the TSS values provide data to support modelling the flow velocities and discharge rates within the ABMs. The data obtained from the excavations, hydrological and aerial surveys conducted in the South Fields supported the modelling of water flows within channels and sediment capture in the stone-bound sediment trap fields within the North fields. Incorporating the decision-making strategies employed by the communities from the interviews and focus group studies, the agent-based model is able to provide insights into how the system functioned and how farmer decision-making allowed them to adapt to various circumstances overtime.

In the model conceptualisation (Chapter Three), the wide range of factors and dynamics that influenced the development of the Engaruka system presented a variety of challenges in developing an agent-based model that could effectively represent the system's dynamics and complexity. The two main factors were the complexity required and the scales of interactions for different factors. Given the wide range of factors that influence a complex system, incorporating such a wide range could result in the incorporation of assumptions that might not adequately reflect the system being studied or provide useful outputs (Barreteau *et al.* 2004, 261; Wainwright and Mulligan 2004, 8; Holling 2001, 390). In order to prevent incorporation of assumptions and pathways to complexity that might not be relevant to the model or clear from the information available (An 2012, 25), the model processes were simplified to the main processes that influence the system in order to build understanding of the system, rather than creating a fully controlled system that hypothesises cause-and-effect. The challenge of scale both temporally and spatially also had to be taken into consideration where spatial resolutions ranged from finer resolution scales of 36 m^2 for a single sediment trap field to landscape scales of 3.5 km^2 for the South Fields and 9 km^2 for the North Fields of the historical Engaruka system. In addition, temporal scales ranged from daily to monthly and annually as well as decadal and centurial time-scales.

In order to represent the finer scale processes and interactions that influence sediment transport and irrigation canal hydraulic dynamics, the Engaruka Sediment Transport and Capture (ESTRaP) model was developed. The ESTRaP model addresses the finer scale issues of sediment transport within a section of the North Fields system by assessing the influence of water and sediment discharge on sediment accumulation rates in the fields. In order to address the broader landscape and long-term scales of human decision-making and the development and expansion of the Engaruka water-management system, the Techniques of Irrigation Management in Engaruka: Modelling Agricultural Choices in Nascent Economies (TIME-MACHINE) model was developed. The TIME-MACHINE model explores the use of rain-fed and irrigation agriculture and the influence of climate variability and social norms on the development and continued use of the system as well as its long-term resilience and sustainability. These models were used to assess the dynamics of the historical system where the environmental and human factors can be analysed and interrelated over a spatial and temporal scale across multiple scenarios. The design and implementation of two ABMs therefore facilitates the exploration of the factors that influenced the development of the historic Engaruka system at the different spatial and temporal scales. The outcomes from the implementation of the different scenarios provide insights into the factors that influenced the development and continued use of the system. In addition the emerging patterns from the models and the performance of the models in simulating real-world scenarios as well as developing realistic outcomes is discussed. In this way, the models can inform our understanding of the sustainability of the system and the application of the lessons learnt to contemporary systems.

The ESTRaP model simulates the effect of different climate scenarios on water availability for the transport of water and sediments within a canal network linking a block of 90 6 × 6 m sediment trap fields covering approximately 3,000 m^2 of the North Fields. The block of fields simulated in the model took between 1 - 2 months to accumulate sediments to depths of 350 mm, while to accumulate sediments to depths of 700 mm it would take farmers 2 - 3 months. The timescales estimated could then be expanded to provide estimates of the time it would take to construct fields sequentially across the system. The model results in Chapter Four showed that would take between 8 - 13 years to construct a block of fields covering 3,000 m^2 for sediment depths of 350 mm, which means that if field blocks were constructed sequentially, it would take between 24,000 – 39,000 years to construct the fields to cover the entire 9 km^2 of the North Fields. Given that the North Fields is only part of the 20 km^2 Engaruka field system, and that the known occupation is between 15th -18th centuries CE, these timelines far exceed the known occupation of the site and do not account for further expansion into the rest of the site. Thus the model demonstrates that the field system was constructed in concurrent rather than sequential blocks by different households across the landscape, with farmers able to construct individual 6 × 6 m fields within a short period of time.

The TIME-MACHINE model simulates the effect of different climate scenarios and human scenarios on Rain-fed and Irrigated agriculture to assess the dynamics that influenced the development and continued use of the Engarukan system. Results of the simulations show that the Irrigated scenarios resulted in higher yields as compared to the Rain-fed-SI scenarios under current climate simulations. The Irrigated scenarios resulted in yields of 13, 000kg ha^{-1} per field as compared to the Rain-fed-SI results of 10,000 kg ha^{-1} per field; however, the Irrigated practices came at a higher energy cost of 2,200 MJ a^{-1} as compared to the Rain-fed-SI at 1,500 MJ a^{-1}. The higher yields from irrigated agriculture makes it an attractive option where there is little room to expand the area under cultivation (Wallace 2000; Boserup 1965). Given the higher inputs required, failures in crop productivity under the Irrigated scenario would have more damaging impacts to the farmer-households who invested more energy in the hopes for increased yields that failed to materialise. Simulations for different climate conditions (TM-01 – TM-05) under the Rain-fed-SI and Irrigated scenarios further explored the effect of each of these practices on the area planted by the farmer-households and ultimately on the patterns and timescales of field expansion. Under the Rain-fed-SI scenario the farmers would plant an average of 90 fields and when utilising supplemental irrigation could increase that area to up to 200 fields, while under the Irrigated scenario farmers planted an average of 50 fields. Given the area of each field was 900m^2 the farmer households were cultivating between 45,000 - 81,000 m^2 each year and as high as 180,000 m^2. Under different climate scenarios, the area planted further varied from year to year, ranging from 23 - 98 fields to cover an area of 20,700 – 88,200 m^2. While the ESTRaP model provides better data on the construction and expansion of the sediment trap fields, the TIME-MACHINE model can also provide further data based on the area planted by farmers under the different agricultural scenarios of Rain-fed-SI and Irrigated agriculture. The area planted can also be used to estimate the amount of time it would take to construct and expand the fields to cover the entire 3.5km^2 that makes up the South Fields of the Engaruka system. Estimates showed that it would take between 19 years – 169 years to construct the fields. However, these estimates make the assumption that farmers build new fields every year, and also do not take into consideration the time it would take for sediments to accumulate within the fields.

In the TIME-MACHINE model, the impact of alternative activities and social norms point to the factors that could have resulted in the abandonment of the system as well as the factors that influenced its continued use. The simulations for the alternative subsistence activities scenario (TM-06) under different climatic conditions show that under the Irrigated scenarios, farmers continued using the system for longer as compared to the Rain-fed-SI scenarios. However, while farmer-households in the Irrigated scenarios took longer to switch to alternative activities, the transition was more abrupt as compared to those in the Rain-fed-SI scenario. The influence of alternative activities outlined one of the factors that could have led to the abandonment of the Engaruka system whereby the farmers were incentivised to switch to alternative subsistence activities when climatic conditions make crop productivity unfavourable. However, social norms can influence the continued use of the system such that despite the presence of attractive alternative subsistence activities, the farmer-households continue farming. The simulation of the impact of social norms (TM-07) meant that under similar climatic conditions where farmers considered alternatives activities, the farmer households would make the switch, while when the social norms effect was included the majority of farmer-households continued farming. Under Rain-fed-SI scenarios the farmers all switched by Year 78 of the simulation while those under the Irrigated scenario switched by Year 34 if there was no social norms effect. However, in these same climatic scenarios, when the effect of social norms was incorporated, the majority of farmer-households continued farming with only a few households leaving the system. This means that at the end of the simulation in Year 115, 16 farmer-households continued farming and only 3 households left under the Rain-fed-SI scenario, while under the Irrigated scenario 10 households continued farming while 5 households switched to the alternatives. In addition, even in the absence of a social norm effect, the population size influenced the continued use of the system. Under the Rain-fed-SI scenario when there were 50 households, 15 of these households were still farming by Year 115, while in the Irrigated scenario it took longer for all the farmer-households to switch to alternative activities as compared to the scenarios simulating 20 farmer-households.

6.3 Conclusion

The ABMs developed under this research are intended to advance our understanding of the environmental and socioeconomic factors that influenced the development, expansion and continued use of the historical Engaruka water-management system. The models represent first steps in understanding the development of field systems and support archaeological interpretations of the patterns and timescales of field construction and expansion that could not have been inferred from the archaeological evidence. The outputs of the model simulations provide timescales for the expansion of the field system and the rates of sediment accumulation as well as supporting interpretations for the factors that influenced the systems development and eventually, its abandonment. In addition, this information gives us further understanding on whether the system was developed through large-scale expansions or through smaller scale iterations of construction that eventually led to the development of the entire field system. This further narrows down the factors and patterns of field development, such as the concurrent construction of the fields and sediment accumulation as demonstrated by ESTRaP. As well as small-scale iterations of field expansion as shown by TIME-MACHINE, that could have eventually led to the development of the entire complex of fields and irrigation canals that are now observed in the archaeology. The model results support archaeological interpretations where despite the available information, we cannot provide information on the sediment rates if we only relied on the archaeological data, and therefore we could only hypothesise about how the community may have behaved. The modelling allows us to explore the effects of different variables and conditions that support can archaeological interpretations, making these models particularly relevant to other sites and studies for which similar data constraints exist.

The ESTRaP model supports archaeological and geoarchaeological interpretations put forward by Lang and Stump (2017) and Stump (2006a) by demonstrating that the sediments could be transported by low water flows and accumulate incrementally in the fields over successive seasons. Provisional OSL dates place the sediment deposits in the stone-bound fields to between 700 ± 120 CE to 1860 ± 110 CE. Comparing these OSL dates with model outputs that highlight the fact that construction of the fields in a sequential manner far exceeds the timelines for which the fields were constructed as compared to if the fields were constructed in concurrent blocks, thus highlighting the model's ability to support archaeological interpretations (see section 4.6). These model results demonstrate that the construction of fields and accumulation of sediments could be a manageable endeavour carried out by a few farmer-households working with small volumes of sediment at a time. In addition, the estimations for the time it would take to develop a block of fields point towards patterns of concurrent development of blocks of fields across the landscape rather than sequential.

The TIME-MACHINE model supports interpretations of the effect of employment of expansive and intensive agricultural practices on the expansion and continued use of the system. The results point to small-scale field development iterated over time by a small number of farmer-households that eventually results in a complex system of irrigation canals and sediment trap fields (see also Bevan and Conolly 2011, 1313). This differs from the expectation that such a complex irrigation system would need to be built through large-scale expansion. The patterns of field expansion and contraction also support interpretations that the field system could be built when needed but left to fallow for long periods as shown by similar farming systems in the region such as in Konso and Marakwet (Ferro-Vázquez *et al.* 2017; Davies *et al.* 2014). This debunks the assumption that the entire field system would be in use at all times and highlights that the system could have been built by a small number of households over time.

The impact of social norms and population size provide further factors for the continued use of the system such that despite the attractiveness of alternative subsistence activities, famer-households continue to utilise the system. In trying to understand the factors that led to the system's eventual abandonment, the models show that it could have been a combination of interacting factors, rather than system collapse through mismanagement. The results of the simulations point to the use of Rain-fed agriculture with supplemental irrigation resulting in long-term continued use of the Engaruka system. This would have allowed the farmer-households to expand their field systems while maintaining productivity through the use of supplemental irrigation, but due to stresses such as prolonged dry conditions, and the influence of social norms, the system may have likely become more reliant on irrigated agriculture to allow the households to continue farming. However, if the farmers eventually became locked in a rigid system that was completely reliant on irrigated agriculture, they would have been more vulnerable to environmental or social stresses. One such stress would be the loss or reduced access to water resources such as the drying up of the rivers that provide the irrigation water (Sutton 1998). In this way the model not only supports interpretations of archaeological evidence for the system's development but also points towards future areas of further study into the factors that influenced the system's abandonment.

The ABMs developed in this research represent first steps in the integration of archaeological evidence with ABM techniques in order to understand the Engaruka site. This research shows how the integration of data from different sources and disciplines can help in our understanding of how the system could have developed by integrating a multitude of factors and showing how these interactions influenced the development of the system. The research develops replicable techniques that combine archaeological evidence with agent-based modelling in order to meet the research aim as well as providing techniques for the assessment of other similar historical systems.

6.3.1 Research Limitations

The models developed explore the factors that influenced the development and expansion of the Engaruka system; however they only cover certain aspects which limit interpretation of the results. The overall limitation that constitutes part of the reason for the development of these models is the limited data available for model inputs, both for the region and for the time periods of the study. There exists limited historical information on the environmental factors such as climate and vegetation dynamics in the Engaruka region at fine resolution. Much of the climate data utilised in the models was based on contemporary data obtained from the CRU high resolution time series (Harris *et al.* 2014) and then combined with interpretations of the palaeoenvironmental proxies for the region (Gelorini and Verschuren 2013; Verschuren *et al.* 2000) to provide climate models. However, the effect of localised climate variations (Marchant *et al.* 2018, 323) could result in further climate variability that would have affected Engaruka and its immediate environs. While these palaeoclimatic models provide estimates for the wider region and can capture more extreme and long-term climate events, the localised effects might not be captured which might have affected the dynamics within the Engaruka system. There is also no known ethnographic record of the community that occupied the system, as well as no records from descendants of the community that can provide ethnographic information on the practices employed. While the ethnographic information from analogous systems such as Konso (as well as the perceptions and strategies of the contemporary Engaruka community) can provide some direction on human decision-making involved, these are only a small sample of the decision-making involved in irrigation practices. The model therefore provides more general aspects of decision-making from behavioural concepts guided by the ethnographic information.

The ESTRaP model focuses on the effect of water availability driving sediment accumulation but other factors are not incorporated, such as the variability in total suspended sediments and the effect of the incorporation of additional field blocks. The variability in sediments is an important consideration as the linear relationship between water and sediment discharge is less clear in real-world estimations (Gray and Simões 2008). In addition, the model focuses on sediment accumulation within one block of fields and does not explore the effect that having a multitude of field blocks within the canal network would have on water and sediment transport and distribution, and thus the rates of sediment accumulation within the field system. Future work to improve the models would involve incorporation of scenarios of variations in TSS and additional field blocks to the model landscape to explore the effect on sediment accumulation rates and timescales for the development of the fields.

The TIME-MACHINE model simulates farmer decision-making based on decision-making concepts from a narrow range of data and concepts of bounded rationality and BDI. This limited data on human decision-making only partly addresses the different behaviour that would have influenced the development of the field system. The factors that guide decision-making tend not to be independent and can incorporate a multitude of objectives (Janssen and van Ittersum 2007). In this model, the focus was on subsistence farming but future work could incorporate additional criteria that explore their choices in agricultural practices, such as accumulation of grain through use of grain stores and trade in yield surpluses, and their objectives as well as conflicting objectives among households. The model incorporates the application of irrigation water as an abstraction rather than through spatially explicit canal networks expressed as agents. The placement of irrigation canals relates to the placement of fields and as such the placement of irrigation canals would affect the construction and expansion of the field system. Therefore incorporating spatially explicit canal networks would enhance further understanding of the patterns of field expansion.

The models are limited in further exploration of the timescale involved in field development and expansion. While each of the models provides results that can enhance archaeological interpretations of the expansion of the field system, the results from the two models do not feed into each other. Because these models are not coupled or fully integrated into one another, timescales in each of the models cannot be integrated to discuss field expansion in combination with sediment accumulation in the fields. There is therefore opportunity for future development of an integrated model that combines both these models at both the finer and coarser resolutions of spatial and temporal scales e.g. through the use of Repast (North *et al.* 2013) as a modelling language.

6.3.2 Towards model performance

It is important to note that the models developed and the results generated are exploratory and further work into their robustness in replicating model outcomes is needed. This forms an integral part of facilitating model performance testing and involves conducting uncertainty analyses that assess the probabilities of attaining similar model results over a series of simulations and model iterations. Future steps in the development of research publications will involve simulating multiple runs of the model scenarios and conducting Markov Chain analyses of runs to determine the probability of replicating the results (Izquierdo *et al.* 2009). These analyses would further inform our understanding of the dynamics incorporated into the models and enhance our understanding of the different ways in which the factors simulated would have interacted.

6.4 Research Impact and Recommendations

This thesis has demonstrated that the models developed can enhance our understanding of the sustainability of the historical Engaruka system by exploring the responses of the farmer-households to different environmental and social factors, how they could have affected their continued use of the system, and the interaction of factors that affected their resilience in the face of extreme environmental or social pressures that could have resulted in system collapse. The research conducted has led to the development of ABMs that, combined with archaeological data, provide tools that advance the understanding of the timescales and patterns of field constructions. Recommendations for future research include combining these models and the model outputs with further research into stratigraphic sequencing and carbon dating to further improve interpretations of the temporal scales involved in the development of the field system.

The research conducted further elucidates the interaction of factors that point to the Engaruka system's sustainability, and that the there is no reason to see resource mismanagement as a prerequisite for abandonment, but rather the model suggests that minor changes in a combination of environmental and social factors could be the reason for its abandonment. This research has outlined the practices that could have enhanced the sustainability of the system and provides direction for recommendations to be proposed to development agencies for the design of agricultural practices and strategies based on the lessons learnt from the historical Engaruka system. These recommendations include the development of policy briefs and collaborative workshops that present concepts on the use of supplemental irrigation as a pathway to increasing productivity while facilitating system sustainability. In addition, strategy and development reports that outline the feasibility of smaller-scale, incremental development of irrigation systems can be developed to support development agendas that would help reduce initialisation costs that usually affect large scale irrigation schemes. In this way the research provides tools for the development of applicable practices in other present-day water-management systems.

6.5 Future Research

The findings from the research inform our understanding of the Engaruka system, how it developed and the interaction of factors that influenced its development and continued use. The ESTRaP model demonstrates that sediment accumulation within a 6 × 6 m field can take place in the relatively short period of a single season, which could be managed by a small number of farmer households constructing blocks of fields concurrently across the landscape; leading to the complex network of irrigated fields at Engaruka. The TIME-MACHINE model demonstrates that there was not necessarily a catastrophic climatic or environmental event that accounts for the abandonment of the historical Engaruka system, but rather a combination of environmental and social factors could have influenced the farmer households into giving up agriculture for alternative subsistence activities on a household to household basis. It can be argued, based on the model results, that the continued use of the Engaruka system was likely due to the potential sustainability of the irrigated agriculture practices, as well as social norms and population size that influenced social cohesion. Such that, where environmental factors could have made alternative subsistence activities more attractive to farmers, the social cohesion generated by social norms and having a larger population of households would have greatly increased the socioeconomic resilience of the system.

The research conducted, while addressing some of the questions on the Engaruka system, presents others that can form part of future research:

- The research can be expanded to integrate the two models so as to assess the dynamics of sediment accumulation at field scale would influence field expansion across the landscape as well as the continued use of the system.
- The research can also be expanded to incorporate actor-network theories (ANT) that extend the human decision-making within the models and assess how human interactions with irrigation infrastructure are influenced by the organisational hierarchies at household, community and state level. The use of ANT is so as to expand the human behaviour beyond artefacts that are predefined behaviours to agent interactions that are emergent (McGlade 2014), focus on the activities involved in irrigation management practices, reducing

the predefined patterns and behaviours to allow for emergent properties to arise.

- Future work can also explore some of the mechanisms that influenced the farmers' choices in moving from extensive to intensive agriculture such as the topographical restrictions of the Engaruka landscape, the presence of hostile neighbours, or centralised social hierarchies that include elites.
- Future research into the effects of tipping points in population sizes on the abandonment of the Engaruka system could also be explored. While the larger population size increased social cohesion, where the number of neighbours enforced a cultural preference to continue farming, the threshold at which this number stops influencing the farmers and the remaining households rapidly abandon the system is not clearly understood.

The research conducted has helped improve our knowledge of the Engaruka system and can be expanded further into the areas recommended above, not only to support further understanding of how this system developed, but also applied to other historic water-management systems globally, and even to address present-day water-management and development research.

References

Abedini, M., Md Said, M. A. & Ahmad, F. 2012. Effectiveness of check dam to control soil erosion in a tropical catchment (The Ulu Kinta Basin). *CATENA,* 97**,** 63-70.

Adams, W. M. 1989. Definition and development in African indigenous irrigation. *AZANIA: Journal of the British Institute in Eastern Africa,* 24**,** 21-27.

Adams, W. M. 1991. Large Scale Irrigation in Northern Nigeria: Performance and Ideology. *Transactions of the Institute of British Geographers,* 16**,** 287-300.

Adams, W. M. & Anderson, D. M. 1988. Irrigation before Development: Indigenous and Induced Change in Agricultural Water Management in East Africa. *African Affairs,* 87**,** 519-535.

Adams, W. M., Potkanski, T. & Sutton, J. E. G. 1994. Indigenous Farmer-Managed Irrigation in Sonjo, Tanzania. *The Geographical Journal,* 160**,** 17-32.

Agnew, C. & Anderson, E. W. 1992. *Water Resources in the Arid Realm*, Routledge.

Ajzen, I. 1991. The theory of planned behavior. *Organizational Behavior and Human Decision Processes,* 50**,** 179-211.

Aktipis, C. A., Cronk, L. & de Aguiar, R. 2011. Risk-Pooling and Herd Survival: An Agent-Based Model of a Maasai Gift-Giving System. *Human Ecology,* 39**,** 131-140.

Alasuutari, P., Bickman, L. & Brannen, J. 2008. *The SAGE handbook of social research methods*, Sage.

Alley, W. M. 2009. Ground Water. *In:* Likens, G. E. (ed.) *Encyclopedia of Inland Waters.* Oxford: Academic Press.

Altaweel, M. & Watanabe, C. E. 2012. Assessing the resilience of irrigation agriculture: applying a social–ecological model for understanding the mitigation of salinization. *Journal of Archaeological Science,* 39**,** 1160-1171.

Amborn, H. 1989. Agricultural intensification in the Burji-Konso cluster of south-western Ethiopia. *AZANIA: Journal of the British Institute in Eastern Africa,* 24**,** 71-83.

An, L. 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling,* 229**,** 25-36.

Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P. & Castroviejo, J. 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. *CATENA,* 128**,** 122-134.

Arnold, J. G., Allen, P. M. & Bernhardt, G. 1993. A comprehensive surface-groundwater flow model. *Journal of Hydrology,* 142**,** 47-69.

Arthur, W. B. 1994. Inductive Reasoning and Bounded Rationality. *The American Economic Review,* 84**,** 406-411.

Asseng, S., Dray, A., Perez, P. & Su, X. 2010. Rainfall–human–spatial interactions in a salinity-prone agricultural region of the Western Australian wheat-belt. *Ecological Modelling,* 221**,** 812-824.

Axtell, R. L., Epstein, J. M., Dean, J. S., Gumerman, G. J., Swedlund, A. C., Harburger, J., Chakravarty, S., Hammond, R., Parker, J. & Parker, M. 2002. Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences,* 99**,** 7275-7279.

Baggio, J. A. & Janssen, M. A. Comparing agent-based models on experimental data of irrigation games. Simulation Conference (WSC), 2013 Winter, 8-11 Dec. 2013 2013. 1742-1753.

Balke, T. & Gilbert, N. 2014. How Do Agents Make Decisions? A Survey. *Journal of Artificial Societies and Social Simulation,* 17**,** 13.

Barbour, R. S. 2001. Checklists for improving rigour in qualitative research: a case of the tail wagging the dog? *BMJ : British Medical Journal,* 322**,** 1115-1117.

Barker, P. & Gasse, F. 2003. New evidence for a reduced water balance in East Africa during the Last Glacial Maximum: implication for model-data comparison. *Quaternary Science Reviews,* 22**,** 823-837.

Barreteau, O., Bousquet, F., Millier, C. & Weber, J. 2004. Suitability of Multi-Agent Simulations to study irrigated system viability: application to case studies in the Senegal River Valley. *Agricultural Systems,* 80**,** 255-275.

Barton, C., Ullah, I. & Heimsath, A. 2015. How to Make a Barranco: Modeling Erosion and Land-Use in Mediterranean Landscapes. *Land,* 4**,** 578.

Barton, C. M., Ullah, I. I. & Bergin, S. 2010. Land use, water and Mediterranean landscapes: modelling long-term dynamics of complex socio-ecological systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 368**,** 5275.

Barton, C. M., Ullah, I. I. T., Bergin, S. M., Mitasova, H. & Sarjoughian, H. 2012. Looking for the future in the past: Long-term change in socioecological systems. *Ecological Modelling,* 241**,** 42-53.

Baumann, E., Ball, P. & Beyene, A. 2005. Rationalization of Drilling Operations in Tanzania. *Review of the Borehole Drilling Sector in Tanzania*.

Beckers, B., Berking, J. & Schütt, B. 2013. Ancient water harvesting methods in the drylands of the Mediterranean and Western Asia. *eTopoi. Journal for Ancient Studies*.

Becu, N., Perez, P., Walker, A., Barreteau, O. & Page, C. L. 2003. Agent based simulation of a small catchment water management in northern Thailand: Description of the CATCHSCAPE model. *Ecological Modelling,* 170**,** 319-331.

Benayas, J. R., Martins, A., Nicolau, J. M. & Schulz, J. J. 2007. Abandonment of agricultural land: an overview of drivers and consequences. *CAB reviews: Perspectives in agriculture, veterinary science, nutrition and natural resources,* 2**,** 1-14.

Benson, M. A. & Dalrymple, T. 1967. General field and office procedures for indirect discharge measurements. *Techniques of Water-Resources Investigations.* - ed.

Bertram, J. & Dewar, R. C. 2013. Statistical patterns in tropical tree cover explained by the different water demand of individual trees and grasses. *Ecology,* 94**,** 2138-2144.

Bevan, A. & Conolly, J. 2011. Terraced fields and Mediterranean landscape structure: An analytical case study from Antikythera, Greece. *Ecological Modelling,* 222**,** 1303-1314.

Beven, K., Lamb, R., Quinn, P., Romanowicz, R., Freer, J. & Singh, V. 1995. Topmodel. *Computer models of watershed hydrology.***,** 627-668.

Beven, K. J. 2001. *Rainfall - Runoff Modelling: The Primer*, John Wiley & Sons.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A. & Stroosnijder, L. 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth, Parts A/B/C,* 47–48**,** 139-151.

Bithell, M. & Brasington, J. 2009. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environmental Modelling & Software,* 24**,** 173-190.

Blöschl, G. & Sivapalan, M. 1995. Scale issues in hydrological modelling: A review. *Hydrological Processes,* 9**,** 251-290.

Blunden, J. & Arndt, D. S. 2016. State of the Climate in 2016. *Bulletin of the American Meteorological Society,* 98**,** Si-S280.

Bonabeau, E. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences,* 99**,** 7280-7287.

Börjeson, L. 2004. The history of Iraqw intensive agriculture. *In:* Widgren, M. & Sutton, J. E. G. (eds.) *Islands of intensive agriculture in Eastern Africa. Past and present.* Oxford: James Currey.

Börjeson, L. 2007. Boserup Backwards? Agricultural Intensification as 'Its Own Driving Force' in the Mbulu Highlands, Tanzania. *Geografiska Annaler. Series B, Human Geography,* 89**,** 249-267.

Boserup, E. 1965. The condition of agricultural growth. *The Economics of Agrarian Change under Population Pressure. Allan and Urwin, London*.

Bronstert, A. & Plate, E. J. 1997. Modelling of runoff generation and soil moisture dynamics for hillslopes and micro-catchments. *Journal of Hydrology,* 198**,** 177-195.

Butzer, K. W. & Endfield, G. H. 2012. Critical perspectives on historical collapse. *Proceedings of the National Academy of Sciences of the United States of America,* 109**,** 3628-3631.

Cai, X., Zhang, X., Noël, P. H. & Shafiee-Jood, M. 2015. Impacts of climate change on agricultural water management: a review. *Wiley Interdisciplinary Reviews: Water,* 2**,** 439-455.

Caretta, M. A. 2015. Hydropatriarchies and landesque capital: a local gender contract analysis of two smallholder irrigation systems in East Africa. *The Geographical Journal,* 181**,** 388-400.

Carleton, T. A. & Hsiang, S. M. 2016. Social and economic impacts of climate. *Science,* 353.

Carswell, G. 2002. Farmers and Following: Agricultural Change in Kigezi District, Uganda. *The Geographical Journal,* 168**,** 130-140.

Castilla-Rho, J. C., Mariethoz, G., Rojas, R., Andersen, M. S. & Kelly, B. F. J. 2015. An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems. *Environmental Modelling & Software,* 73**,** 305-323.

Cegielski, W. H. & Rogers, J. D. 2016. Rethinking the role of Agent-Based Modeling in archaeology. *Journal of Anthropological Archaeology,* 41**,** 283-298.

Chow, T. V. 1959. *Open-channel hydraulics*, McGraw-Hill.

Chu, X. & Steinman, A. 2009. Event and Continuous Hydrologic Modeling with HEC-HMS. *Journal of Irrigation and Drainage Engineering,* 135**,** 119-124.

Cialdini, R. B., Kallgren, C. A. & Reno, R. R. 1991. A focus theory of normative conduct: A theoretical refinement and reevaluation of the role of norms in human behavior. *Advances in experimental social psychology.* Elsevier.

Conelly, W. T. 1994. Population Pressure, Labor Availability, and Agricultural Disintensification: The Decline of Farming on Rusinga Island, Kenya. *Human Ecology,* 22**,** 145-170.

Costanza, R., Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., Leemans, R., Redman, C. & Schimel, D. 2007. Sustainability or collapse: What can we learn from integrating the history of humans and the rest of nature? *AMBIO: A Journal of the Human Environment,* 36**,** 522-527.

Costanza, R. & Patten, B. C. 1995. Defining and predicting sustainability. *Ecological Economics,* 15**,** 193-196.
Crabtree, S. A. & Kohler, T. A. 2012. Modelling across millennia: Interdisciplinary paths to ancient socio-ecological systems. *Ecological Modelling,* 241**,** 2-4.
Critchley, W. & Siegert, K. 1991. Water harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. Rome, Italy: Food and Agriculture Organization of the United Nations.
Crooks, A. & Heppenstall, A. 2012. Introduction to Agent-Based Modelling. *In:* Heppenstall, A. J., Crooks, A. T., See, L. M. & Batty, M. (eds.) *Agent-Based Models of Geographical Systems.* Springer Netherlands.
d'Oleire-Oltmanns, S., Marzolff, I., Peter, K. D. & Ries, J. B. 2012. Unmanned Aerial Vehicle (UAV) for monitoring soil erosion in Morocco. *Remote Sensing,* 4**,** 3390-3416.
D'Onofrio, D., Baudena, M., D'Andrea, F., Rietkerk, M. & Provenzale, A. 2015. Tree-grass competition for soil water in arid and semiarid savannas: The role of rainfall intermittency. *Water Resources Research,* 51**,** 169-181.
Davie, T. 2008. *Fundamentals of Hydrology*, Routledge.
Davies, M. 2015. Economic specialisation, resource variability, and the origins of intensive agriculture in Eastern Africa. *Rural Landscapes: Society, Environment, History,* 2.
Davies, M. I. J. 2010. From platforms to people: rethinking population estimates for the abandoned agricultural settlement at Engaruka, northern Tanzania. *Azania: Archaeological Research in Africa,* 45**,** 203-213.
Davies, M. I. J., Kipruto, T. K. & Moore, H. L. 2014. Revisiting the irrigated agricultural landscape of the Marakwet, Kenya: tracing local technology and knowledge over the recent past. *Azania: Archaeological Research in Africa,* 49**,** 486-523.
Dawson, J. B. 2008. *The Gregory Rift Valley and Neogene-recent Volcanoes of Northern Tanzania*, Geological Society.
de Ridder, N. & van Keulen, H. 1995. Estimating biomass through transfer functions based on simulation model results: a case study for the Sahel. *Agricultural Water Management,* 28**,** 57-71.
Devia, G. K., Ganasri, B. P. & Dwarakish, G. S. 2015. A Review on Hydrological Models. *Aquatic Procedia,* 4**,** 1001-1007.
Dixon, J., Stringer, L. & Challinor, A. 2014. Farming System Evolution and Adaptive Capacity: Insights for Adaptation Support. *Resources,* 3**,** 182.
Erickson, C. L. 2006. Intensification, political economy, and the farming community; in defense of a bottom-up perspective of the past.
Ertsen, M. W., Murphy, J. T., Purdue, L. E. & Zhu, T. 2014. A journey of a thousand miles begins with one small step - human agency, hydrological processes and time in socio-hydrology. *Hydrol. Earth Syst. Sci.,* 18**,** 1369-1382.
Evenari, M., Shanan, L. & Tadmor, N. 1982. *The Negev: the challenge of a desert*, Harvard University Press.
FAO 2002. Yield Response to Water: the original FAO water production function. Food and Agriculture Organization of the United Nations.
Feola, G. & Binder, C. R. 2010. Towards an improved understanding of farmers' behaviour: The integrative agent-centred (IAC) framework. *Ecological Economics,* 69**,** 2323-2333.

Ferro-Vázquez, C., Lang, C., Kaal, J. & Stump, D. 2017. When is a terrace not a terrace? The importance of understanding landscape evolution in studies of terraced agriculture. *Journal of Environmental Management,* 202**,** 500-513.
Gassman, P. W., Reyes, M. R., Green, C. H. & Arnold, J. G. 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE,* 50**,** 1211-1250.
Gelorini, V. & Verschuren, D. 2013. Historical climate-human-ecosystem interaction in East Africa: a review. *African Journal of Ecology,* 51**,** 409-421.
Gigerenzer, G. & Selten, R. 2002. *Bounded rationality: The adaptive toolbox*, MIT press.
Giráldez, J. V., Ayuso, J. L., Garcia, A., López, J. G. & Roldán, J. 1988. Water harvesting strategies in the semiarid climate of southeastern Spain. *Agricultural Water Management,* 14**,** 253-263.
Giusti, E. & Marsili-Libelli, S. 2015. A Fuzzy Decision Support System for irrigation and water conservation in agriculture. *Environmental Modelling & Software,* 63**,** 73-86.
Glaser, B. G. 1998. *Doing Grounded Theory: Issues and Discussions*, Sociology Press.
Gómez-Limón, J. A., Berbel, J. & Arriaza, M. 2007. MCDM farm system analysis for public management of irrigated agriculture. *In:* Weintraub, A., Romero, C., Bjørndal, T., Epstein, R. & Miranda, J. (eds.) *Handbook Of Operations Research In Natural Resources.* Springer.
Goodrich, D., Bums, I., Unkrich, C., Semmens, D., Guertin, D., Hernandez, M., Yatheendradas, S., Kennedy, J. & Levick, L. 2012. KINEROS 2/AGWA: Model use, calibration, and validation. *Transactions of the ASABE,* 55**,** 1561-1574.
Gordon, N. D., McMahon, T. A. & Finlayson, B. L. 2004. *Stream hydrology: an introduction for ecologists*, John Wiley and Sons.
Gray, J. R. & Simões, F. J. 2008. Estimating sediment discharge. *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice.*
Graybiel, A. M. 2008. Habits, Rituals, and the Evaluative Brain. *Annual Review of Neuroscience,* 31**,** 359-387.
Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jørgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., Robbins, M. M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R. A., Vabø, R., Visser, U. & DeAngelis, D. L. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling,* 198**,** 115-126.
Groeneveld, J., Müller, B., Buchmann, C. M., Dressler, G., Guo, C., Hase, N., Hoffmann, F., John, F., Klassert, C., Lauf, T., Liebelt, V., Nolzen, H., Pannicke, N., Schulze, J., Weise, H. & Schwarz, N. 2017. Theoretical foundations of human decision-making in agent-based land use models – A review. *Environmental Modelling & Software,* 87**,** 39-48.
Gunderson, L. H. 2000. Ecological Resilience--In Theory and Application. *Annual Review of Ecology and Systematics,* 31**,** 425-439.
Håkansson, T. 2008. Regional Political Ecology and Intensive Cultivation in Pre-Colonial and Colonial South Pare, Tanzania. *The International Journal of African Historical Studies,* 41**,** 433-459.
Hallpike, C. R. 2008. *The Konso of Ethiopia : A study of the values of an East Cushitic People,* United States of America, AuthorHouse.

Hannaford, M. J., Bigg, G. R., Jones, J. M., Phimister, I. & Staub, M. 2014. Climate Variability and Societal Dynamics in Pre-Colonial Southern African History (AD 900-1840): A Synthesis and Critique. *Environment and History,* 20, 411-445.

Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology,* 34, 623-642.

Harrower, M. J. 2008. Hydrology, ideology, and the origins of irrigation in ancient Southwest Arabia. *Current Anthropology,* 49, 497-510.

Harrower, M. J. 2010. Geographic Information Systems (GIS) hydrological modeling in archaeology: an example from the origins of irrigation in Southwest Arabia (Yemen). *Journal of Archaeological Science,* 37, 1447-1452.

Hassan, R. M. & Nhemachena, C. 2008. Determinants of African farmersâ€™ strategies for adapting to climate change: Multinomial choice analysis. *African Journal of Agricultural and Resource Economics,* 2, 83-104.

Heath, H. & Cowley, S. 2004. Developing a grounded theory approach: a comparison of Glaser and Strauss. *International Journal of Nursing Studies,* 41, 141-150.

Heckbert, S., Isendahl, C., Gunn, J. D., Brewer, S., Scarborough, V. L., Chase, A. F., Chase, D. Z., Costanza, R., Dunning, N. P., Beach, T., Luzzadder-Beach, S., Lentz, D. & Sinclair, P. 2016. Growing the Ancient Maya Social-Ecological System from the Bottom Up. *In:* Isendahl, C. & Stump, D. (eds.) *The Oxford Handbook of Historical Ecology and Applied Archaeology.* Oxford Handbooks Online: Oxford University Press.

Heppenstall, A., Malleson, N. & Crooks, A. 2016. "Space, the Final Frontier": How Good are Agent-Based Models at Simulating Individuals and Space in Cities? 4, 9.

Hession, S. L. & Moore, N. 2011. A spatial regression analysis of the influence of topography on monthly rainfall in East Africa. *International Journal of Climatology,* 31, 1440-1456.

Hill, J. & Woodland, W. 2003. Contrasting water management techniques in Tunisia: towards sustainable agricultural use. *The Geographical Journal,* 169, 342-357.

Holling, C. S. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems,* 4, 390-405.

Homewood, K. M. & Rodgers, W. A. 1991. *Maasailand ecology: pastoralist development and wildlife conservation in Ngorongoro, Tanzania*, Cambridge University Press.

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology,* 56, 79-94.

Hudson, N. 1993. *Field measurement of soil erosion and runoff*, Food & Agriculture Org.

Hugenholtz, C. H., Whitehead, K., Brown, O. W., Barchyn, T. E., Moorman, B. J., LeClair, A., Riddell, K. & Hamilton, T. 2013. Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. *Geomorphology,* 194, 16-24.

Isern, D., Abelló, S. & Moreno, A. 2012. Development of a multi-agent system simulation platform for irrigation scheduling with case studies for garden irrigation. *Computers and Electronics in Agriculture,* 87, 1-13.

Izquierdo, L. R., Izquierdo, S. S., Galan, J. M. & Santos, J. I. 2009. Techniques to understand computer simulations: Markov chain analysis. *Journal of Artificial Societies and Social Simulation,* 12**,** 6.

Janssen, M. A. 2007. Coordination in irrigation systems: An analysis of the Lansing–Kremer model of Bali. *Agricultural Systems,* 93**,** 170-190.

Janssen, S. & van Ittersum, M. K. 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems,* 94**,** 622-636.

Javernick, L., Brasington, J. & Caruso, B. 2014. Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry. *Geomorphology,* 213**,** 166-182.

Jones, P. & Harris, I. 2008. Climatic Research Unit (CRU) time-series datasets of variations in climate with variations in other phenomena. NCAS British Atmospheric Data Centre.

Kahneman, D. & Tversky, A. 1979. Prospect Theory: An Analysis of Decision under Risk. *Econometrica,* 47**,** 263-291.

Kavanagh, B. F. & Bird, S. G. 2000. *Surveying: Principles and applications*, Prentice Hall Upper Saddle River (NJ).

Kohler, T. A., Bocinsky, R. K., Cockburn, D., Crabtree, S. A., Varien, M. D., Kolm, K. E., Smith, S., Ortman, S. G. & Kobti, Z. 2012. Modelling prehispanic Pueblo societies in their ecosystems. *Ecological Modelling,* 241**,** 30-41.

Koponen, J. 1988. *People and Production in Late Precolonial Tanzania: History and Structures*, Finnish Society for Development Studies.

Lake, M. W. 2014. Trends in Archaeological Simulation. *Journal of Archaeological Method and Theory,* 21**,** 258-287.

Lake, M. W. 2015. Explaining the past with ABM: on modelling philosophy. *Agent-based modeling and simulation in archaeology.* Springer.

Lane, P. 1994. The Use and Abuse of Ethnography in the Study of the Southern African Iron Age. *Azania: Archaeological Research in Africa,* 29-30**,** 51-64.

Lang, C. & Stump, D. 2017. Geoarchaeological evidence for the construction, irrigation, cultivation, and resilience of 15th--18th century AD terraced landscape at Engaruka, Tanzania. *Quaternary Research*, 1-18.

Lansing, J. S. & Kremer, J. N. 1993. Emergent Properties of Balinese Water Temple Networks: Coadaptation on a Rugged Fitness Landscape. *American Anthropologist,* 95**,** 97-114.

Lesschen, J. P., Schoorl, J. M. & Cammeraat, L. 2009. Modelling runoff and erosion for a semi-arid catchment using a multi-scale approach based on hydrological connectivity. *Geomorphology,* 109**,** 174-183.

Linard, J. I., Wolock, D. M., Webb, R. M. & Wieczorek, M. E. 2009. *Identifying hydrologic processes in agricultural watersheds using precipitation-runoff models*, US Geological Survey.

Lu, J., Sun, G., McNulty, S. G. & Amatya, D. M. 2005. A Comparison of Six Potential Evapotranspiration Methods for Regional Use in the Southeastern United States. *JAWRA Journal of the American Water Resources Association,* 41**,** 621-633.

Macal, C. M. & North, M. J. Agent-based modeling and simulation. Winter simulation conference, 2009. Winter Simulation Conference, 86-98.

Macal, C. M. & North, M. J. 2010. Tutorial on agent-based modelling and simulation. *Journal of Simulation,* 4**,** 151-162.

Madella, M., Rondelli, B., Lancelotti, C., Balbo, A., Zurro, D., Campillo, X. R. & Stride, S. 2014. Introduction to Simulating the Past. *Journal of Archaeological Method and Theory,* 21**,** 251-257.

Marchant, R., Richer, S., Boles, O., Capitani, C., Courtney-Mustaphi, C. J., Lane, P., Prendergast, M. E., Stump, D., De Cort, G., Kaplan, J. O., Phelps, L., Kay, A., Olago, D., Petek, N., Platts, P. J., Punwong, P., Widgren, M., Wynne-Jones, S., Ferro-Vázquez, C., Benard, J., Boivin, N., Crowther, A., Cuní-Sanchez, A., Deere, N. J., Ekblom, A., Farmer, J., Finch, J., Fuller, D., Gaillard-Lemdahl, M.-J., Gillson, L., Githumbi, E., Kabora, T., Kariuki, R., Kinyanjui, R., Kyazike, E., Lang, C., Lejju, J., Morrison, K. D., Muiruri, V., Mumbi, C., Muthoni, R., Muzuka, A., Ndiema, E., Kabonyi Nzabandora, C., Onjala, I., Schrijver, A. P., Rucina, S., Shoemaker, A., Thornton-Barnett, S., van der Plas, G., Watson, E. E., Williamson, D. & Wright, D. 2018. Drivers and trajectories of land cover change in East Africa: Human and environmental interactions from 6000 years ago to present. *Earth-Science Reviews,* 178**,** 322-378.

Marston, J. M. 2015. Modeling Resilience and Sustainability in Ancient Agricultural Systems. *Journal of Ethnobiology,* 35**,** 585-605.

Maxwell, R. M., Condon, L. E., Kollet, S. J., Maher, K., Haggerty, R. & Forrester, M. M. 2016. The imprint of climate and geology on the residence times of groundwater. *Geophysical Research Letters,* 43**,** 701-708.

McGlade, J. 2014. Simulation as Narrative: Contingency, Dialogics, and the Modeling Conundrum. *Journal of Archaeological Method and Theory,* 21**,** 288-305.

Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E. M. & Maroulis, J. 2015. Soil Conservation Through Sediment Trapping: A Review. *Land Degradation & Development,* 26**,** 544-556.

Miedema, S. 2010. Constructing the Shields curve, a new theoretical approach and its applications. *WODCON XIX, Beijing China*.

Millington, J. & Wainwright, J. 2016. *Comparative Approaches for Innovation in Agent-Based Modelling of Landscape Change*.

Minnis, P. E. 2004. Extinction Isn't Always Forever: Biodiversity and Prehistory. *In:* Redman, S. R., Fish, P. R. & Rogers, J. D. (eds.) *The archaeology of global change.* Washington DC: Smithsonian Books.

Monroe, K. R. 2001. Paradigm Shift: From Rational Choice to Perspective. *International Political Science Review,* 22**,** 151-172.

Montgomery, D. R. & Buffington, J. M. 1998. Channel processes, classification, and response. *In:* Naiman, R. J. & Bilby, R. E. (eds.) *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion.* New York: Springer.

Moreno-de las Heras, M., Díaz-Sierra, R., Turnbull, L. & Wainwright, J. 2015. Assessing vegetation structure and ANPP dynamics in a grassland–shrubland Chihuahuan ecotone using NDVI–rainfall relationships. *Biogeosciences,* 12**,** 2907-2925.

Morgan, F., Brown, P. & Daigneault, A. 2015. *Simulation vs. Definition: Differing Approaches to Setting Probabilities for Agent Behaviour*.

Morgan, W. T. W. 1974. The South Turkana Expedition: Scientific Papers X. Sorghum Gardens in South Turkana: Cultivation among a Nomadic Pastoral People. *The Geographical Journal,* 140**,** 80-93.

Moriasi, D., Wilson, B., Douglas-Mankin, K., Arnold, J. & Gowda, P. 2012. Hydrologic and water quality models: Use, calibration, and validation. *Transactions of the ASABE,* 55**,** 1241-1247.

Morrison, K. D. 2015. Archaeologies of flow: Water and the landscapes of Southern India past, present, and future. *Journal of Field Archaeology,* 40**,** 560-580.

Mouri, G., Ros, F. C. & Chalov, S. 2014. Characteristics of suspended sediment and river discharge during the beginning of snowmelt in volcanically active mountainous environments. *Geomorphology,* 213**,** 266-276.

Mulder, C. & Hendriks, A. J. 2014. Half-saturation constants in functional responses. *Global Ecology and Conservation,* 2**,** 161-169.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. & Schwarz, N. 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software,* 48**,** 37-48.

Murphy, J. T. 2012. Exploring complexity with the Hohokam Water Management Simulation: A middle way for archaeological modeling. *Ecological Modelling,* 241**,** 15-29.

Mutambara, S., Darkoh, M. B. K. & Atlhopheng, J. R. 2016. A comparative review of water management sustainability challenges in smallholder irrigation schemes in Africa and Asia. *Agricultural Water Management,* 171**,** 63-72.

NASA_JPL 2012. NASA Shuttle Radar Topography Mission (SRTM) Void-Filled 3 arc second. Version 2. 03°S, 35°E. . NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. [DOI: http://dx.doi.org/]

NASA_LP_DAAC 2011. ASTER Global Digital Elevation Model (GDEM) 1 arc second. Version 2. 03°S, 35°E. . NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. [DOI: http://dx.doi.org/10.5067/ASTER/ASTGTM.002]

Nill, D., Schwertmann, U., Sabel-Koschella, U., Berhard, M. B. J. & Breuer, J. 1996. Soil erosion by water in Africa. *Principles, prediction and protection. GTZ, Germany,* 292.

North, M. J., Collier, N. T., Ozik, J., Tatara, E. R., Macal, C. M., Bragen, M. & Sydelko, P. 2013. Complex adaptive systems modeling with Repast Simphony. *Complex Adaptive Systems Modeling,* 1**,** 3.

Nu-Fang, F., Zhi-Hua, S., Lu, L. & Cheng, J. 2011. Rainfall, runoff, and suspended sediment delivery relationships in a small agricultural watershed of the Three Gorges area, China. *Geomorphology,* 135**,** 158-166.

Östberg, W. 2004. The Expansion of Marakwet Hill-Furrow Irrigation in the Kerio Valley of Kenya. *In:* Widgren, M. & Sutton, J. E. G. (eds.) *Islands of intensive agriculture in Eastern Africa. Past and present.* Oxford: James Currey.

Oweis, T. & Hachum, A. 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management,* 80**,** 57-73.

Özerol, G. & Bressers, H. 2017. How do Farmers Align with the Agri-Environmental Changes in Irrigated Agriculture? A Case Study from the Harran Plain, Turkey. *Irrigation and Drainage,* 66**,** 45-59.

Parsons, A. J., Cooper, J. & Wainwright, J. 2015. What is suspended sediment? *Earth Surface Processes and Landforms,* 40**,** 1417-1420.

Pereira, L. S., Oweis, T. & Zairi, A. 2002. Irrigation management under water scarcity. *Agricultural water management,* 57, 175-206.
Pilgrim, D. H., Chapman, T. G. & Doran, D. G. 1988. Problems of rainfall-runoff modelling in arid and semiarid regions. *Hydrological Sciences Journal,* 33, 379-400.
Purdue, L. E. & Berger, J.-F. 2015. An integrated socio-environmental approach to the study of ancient water systems: the case of prehistoric Hohokam irrigation systems in semi-arid central Arizona, USA. *Journal of Archaeological Science,* 53, 586-603.
Ramos, M. C., Cots-Folch, R. & Martínez-Casasnovas, J. A. 2007. Sustainability of modern land terracing for vineyard plantation in a Mediterranean mountain environment – The case of the Priorat region (NE Spain). *Geomorphology,* 86, 1-11.
Ran, D.-C., Luo, Q.-H., Zhou, Z.-H., Wang, G.-Q. & Zhang, X.-H. 2008. Sediment retention by check dams in the Hekouzhen-Longmen Section of the Yellow River. *International Journal of Sediment Research,* 23, 159-166.
Reaney, S. M. 2008. The use of agent based modelling techniques in hydrology: determining the spatial and temporal origin of channel flow in semi-arid catchments. *Earth Surface Processes and Landforms,* 33, 317-327.
Reaney, S. M., Bracken, L. J. & Kirkby, M. J. 2007. Use of the Connectivity of Runoff Model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas. *Hydrological Processes,* 21, 894-906.
Rhodes, D. M., Holcombe, M. & Qwarnstrom, E. E. 2016. Reducing complexity in an agent based reaction model—Benefits and limitations of simplifications in relation to run time and system level output. *Biosystems,* 147, 21-27.
Rietkerk, M., Boerlijst, M. C., Langevelde, F. v., HilleRisLambers, R., Koppel, J. v. d., Kumar, L., Prins, H. H. T. & Roos, A. M. d. 2002. Self-Organization of Vegetation in Arid Ecosystems. *The American Naturalist,* 160, 524-530.
Rietkerk, M. & Koppel, J. v. d. 1997. Alternate Stable States and Threshold Effects in Semi-Arid Grazing Systems. *Oikos,* 79, 69-76.
Rippin, D. M., Pomfret, A. & King, N. 2015. High resolution mapping of supra-glacial drainage pathways reveals link between micro-channel drainage density, surface roughness and surface reflectance. *Earth Surface Processes and Landforms*, n/a-n/a.
Risbey, J., Kandlikar, M., Dowlatabadi, H. & Graetz, D. 1999. Scale, context, and decision making in agricultural adaptation to climate variability and change. *Mitigation and Adaptation Strategies for Global Change,* 4, 137-165.
Robert, A. 2014. *River processes: an introduction to fluvial dynamics*, Routledge.
Rockstrom, J. 2000. Water resources management in smallholder farms in Eastern and Southern Africa: An overview. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere,* 25, 275-283.
Rockström, J. & Karlberg, L. 2009. Zooming in on the global hotspots of rainfed agriculture in water-constrained environments. *Rainfed agriculture: unlocking the potential*, 36-43.
Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J. & Qiang, Z. 2010. Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management,* 97, 543-550.

Roy, S. & Mistri, B. 2013. Estimation of Peak Flood Discharge for an Ungauged River: A Case Study of the Kunur River, West Bengal. *Geography Journal,* 2013, 11.

Ryner, M., Holmgren, K. & Taylor, D. 2008. A record of vegetation dynamics and lake level changes from Lake Emakat, northern Tanzania, during the last c. 1200 years. *Journal of Paleolimnology,* 40, 583-601.

Scarborough, V. L. 1991. Water management adaptations in nonindustrial complex societies: an archaeological perspective. *Archaeological method and theory*, 101-154.

Scheiter, S. & Higgins, S. I. 2009. Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Global Change Biology,* 15, 2224-2246.

Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M. A., McAllister, R. R. J., Müller, B., Orach, K., Schwarz, N. & Wijermans, N. 2017. A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics,* 131, 21-35.

Schlüter, M. & Pahl-Wostl, C. 2007. Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin. *Ecology and Society,* 12.

Schut, M., van Asten, P., Okafor, C., Hicintuka, C., Mapatano, S., Nabahungu, N. L., Kagabo, D., Muchunguzi, P., Njukwe, E., Dontsop-Nguezet, P. M., Sartas, M. & Vanlauwe, B. 2016. Sustainable intensification of agricultural systems in the Central African Highlands: The need for institutional innovation. *Agricultural Systems,* 145, 165-176.

Sheridan, M. J. 2002. An Irrigation Intake Is like a Uterus: Culture and Agriculture in Precolonial North Pare, Tanzania. *American Anthropologist,* 104, 79-92.

Sillar, B. & Joffré, G. R. 2016. Using the present to interpret the past: the role of ethnographic studies in Andean archaeology. *World Archaeology,* 48, 656-673.

Simon, H. A. 1972. Theories of bounded rationality. *Decision and organization,* 1, 161-176.

Smith, R., Goodrich, D., Woolhiser, D. & Unkrich, C. 1995. KINEROS–A kinematic runoff and erosion model. *Computer models of watershed hydrology,* 20, 627-668.

Snavely, N., Seitz, S. & Szeliski, R. 2008. Modeling the World from Internet Photo Collections. *International Journal of Computer Vision,* 80, 189-210.

Snavely, N., Seitz, S. M. & Szeliski, R. 2006. Photo tourism: exploring photo collections in 3D. *ACM Trans. Graph.,* 25, 835-846.

Staver, A. C., Archibald, S. & Levin, S. 2011. Tree cover in sub-Saharan Africa: Rainfall and fire constrain forest and savanna as alternative stable states. *Ecology,* 92, 1063-1072.

Steegen, A., Govers, G., Nachtergaele, J., Takken, I., Beuselinck, L. & Poesen, J. 2000. Sediment export by water from an agricultural catchment in the Loam Belt of central Belgium. *Geomorphology,* 33, 25-36.

Stump, D. 2006a. The development and expansion of the field and irrigation systems at Engaruka, Tanzania. *AZANIA: Journal of the British Institute in Eastern Africa,* 41, 69-94.

Stump, D. 2006b. *Towards an applied archaeology of east African intensive agricultural systems.* PhD Doctoral Dissertation, UCL (University College London).

Stump, D. 2010a. "Ancient and backward or long-lived and sustainable?" The role of the past in debates concerning rural livelihoods and resource conservation in eastern Africa. *World Development,* 38, 1251-1262.
Stump, D. 2010b. Intensification in Context: Archaeological Approaches to Precolonial Field Systems in Eastern and Southern Africa. *African Studies,* 69, 255-278.
Stump, D. 2013. The Archaeology of Agricultural Intensification in Africa. *In:* Mitchell, P. & Lane, P. J. (eds.) *The Oxford Handbook of African Archaeology.* Oxford University Press.
Stump, D. 2016. Digging for Indigenous Knowledge: 'Reverse Engineering' and Stratigraphic Sequencing as a Potential Archaeological Contribution to Sustainability Assessments. *In:* Isendahl, C. & Stump, D. (eds.) *The Oxford Handbook of Historical Ecology and Applied Archaeology.* Oxford Handbooks Online: Oxford University Press.
Stump, D. & Tagseth, M. 2009. The history of precolonial and early colonial agriculture on Kilimanjaro: a review. *In:* Clack, T. (ed.) *Culture, History and Identity: Landscapes of Inhabitation in the Mount Kilimanjaro Area.* Oxford: Archaeopress.
Sundborg, Å. 1956. The River Klarälven: A Study of Fluvial Processes. *Geografiska Annaler,* 38, 125-237.
Sutton, J. E. G. 1998. Engaruka: An Irrigation Agricultural Community in Northern Tanzania Before the Maasai. *Azania: Journal of the British Institute in Eastern Africa,* 33, 1-37.
Tagseth, M. 2008. The Expansion of Traditional Irrigation in Kilimanjaro, Tanzania. *The International Journal of African Historical Studies,* 41, 461-490.
Tarolli, P., Preti, F. & Romano, N. 2014. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene,* 6, 10-25.
Tempelhoff, J. W. N. 2008. Historical Perspectives on Pre-Colonial Irrigation in Southern Africa. *African Historical Review,* 40, 121-160.
Thomas, D. S. G., Twyman, C., Osbahr, H. & Hewitson, B. 2007. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change,* 83, 301-322.
Thorngate, W. 2015. Heads and Hearts: Three Methods for Explicating Judgment and Decision Processes. *Journal of Artificial Societies and Social Simulation,* 18, 14.
Thornthwaite, C. W. 1948. An Approach toward a Rational Classification of Climate. *Geographical Review,* 38, 55-94.
Tietjen, B. 2016. Same rainfall amount different vegetation—How environmental conditions and their interactions influence savanna dynamics. *Ecological Modelling,* 326, 13-22.
Tiffen, M., Mortimore, M. & Gichuki, F. 1994. *More people, less erosion: environmental recovery in Kenya*, John Wiley & Sons Ltd.
van Duinen, R., Filatova, T., Jager, W. & van der Veen, A. 2016. Going beyond perfect rationality: drought risk, economic choices and the influence of social networks. *The Annals of Regional Science,* 57, 335-369.
Van Langevelde, F., Van De Vijver, C. A. D. M., Kumar, L., Van De Koppel, J., De Ridder, N., Van Andel, J., Skidmore, A. K., Hearne, J. W., Stroosnijder, L., Bond, W. J., Prins, H. H. T. & Rietkerk, M. 2003. Effects of fire and herbivory on the stability of Savannah ecosystems. *Ecology,* 84, 337-350.

van Rijn, L. C. 1984. Sediment Transport 2: Suspended load transport. *Journal of Hydraulic Engineering-Asce,* 110**,** 1613-1641.
Van Rijn, L. C. 1993. *Principles of sediment transport in rivers, estuaries and coastal seas*, Aqua publications Amsterdam.
van Rijn, L. C. 2013. Sedimentation of Sand and Mud in Reservoirs in Rivers.
Verschuren, D., Laird, K. R. & Cumming, B. F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature,* 403**,** 410-414.
Wainwright, J. 2006. Degrees of separation: Hillslope-channel coupling and the limits of palaeohydrological reconstruction. *CATENA,* 66**,** 93-106.
Wainwright, J. 2008. Can modelling enable us to understand the rôle of humans in landscape evolution? *Geoforum,* 39**,** 659-674.
Wainwright, J. & Mulligan, M. 2003. Modelling human decision making. *In:* Mulligan, M. (ed.) *Environmental Modelling: finding the simplicity in complexity.* Wiley.
Wainwright, J. & Mulligan, M. 2004. *Environmental Modelling: Finding Simplicity in Complexity*, Wiley.
Wainwright, J., Parsons, A. J., Müller, E. N., Brazier, R. E., Powell, D. M. & Fenti, B. 2008. A transport-distance approach to scaling erosion rates: 2. sensitivity and evaluation of Mahleran. *Earth Surface Processes and Landforms,* 33**,** 962-984.
Wainwright, J. & Thornes, J. B. 2004. *Environmental Issues in the Mediterranean: Processes and Perspectives from the Past and Present*, Taylor & Francis.
Wallace, J. S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems & Environment,* 82**,** 105-119.
Watson, E. E. 2009. *Living Terraces in Ethiopia: Konso Landscape, Culture and Development*, Boydell and Brewer.
Weintraub, A., Romero, C., Bjørndal, T., Epstein, R. & Miranda, J. P. 2007. *Handbook of operations research in natural resources*, Springer Science & Business Media.
Westerberg, L.-O., Holmgren, K., BÖrjeson, L., HÅkansson, N. T., Laulumaa, V., Ryner, M. & Öberg, H. 2010. The development of the ancient irrigation system at Engaruka, northern Tanzania: physical and societal factors. *Geographical Journal,* 176**,** 304-318.
Wickham, H. 2009. *ggplot2: Elegant Graphics for Data Analysis*, Springer-Verlag New York.
Widgren, M. 2010. Besieged Palaeonegritics or Innovative Farmers: Historical Political Ecology of Intensive and Terraced Agriculture in West Africa and Sudan. *African Studies,* 69**,** 323-343.
Widgren, M. & Sutton, J. E. G. 2004. *Islands of intensive agriculture in Eastern Africa: past & present*, Oxford: James Currey.
Widomski, M. K. 2011. Terracing as a Measure of Soil Erosion Control and Its effect on improvement of infiltration in eroded environment. *In:* Godone, D. D. (ed.) *Soil Erosion Issues in Agriculture.* INTECH Open Access Publisher.
Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
Wilkinson, S. N., Prosser, I. P. & Hughes, A. O. 2006. Predicting the distribution of bed material accumulation using river network sediment budgets. *Water Resources Research,* 42**,** n/a-n/a.

Wilkinson, T. J., Christiansen, J. H., Ur, J., Widell, M. & Altaweel, M. 2007. Urbanization within a Dynamic Environment: Modeling Bronze Age Communities in Upper Mesopotamia. *American Anthropologist,* 109**,** 52-68.

Woodhouse, P., Veldwisch, G. J., Venot, J.-P., Brockington, D., Komakech, H. & Manjichi, Â. 2017. African farmer-led irrigation development: re-framing agricultural policy and investment? *The Journal of Peasant Studies,* 44**,** 213-233.

Worthman, C. M. Energetics, Sociality, and Human Reproduction: Life History Theory in Real Life. *In:* Wachter, K. W. & Bulatao, R. A., eds. *Offspring: Human Fertility Behavior in Biodemographic Perspective: National Research Council (US) Panel for the Workshop on the Biodemography of Fertility and Family Behavior*, 2003 Washington DC, U.S.: National Academies Press, 289 - 321.

Yu, B., Cakurs, U. & Rose, C. W. 1998. An assessment of methods for estimating runoff rates at the plot scale. *Transactions of the ASAE,* 41**,** 653-661.

Zhang, X., Drake, N. & Wainwright, J. 2002. Scaling land surface parameters for global-scale soil erosion estimation. *Water Resources Research,* 38**,** 19-1-19-9.

Zuazo, V. H. D., Ruiz, J. A., Raya, A. M. & Tarifa, D. F. 2005. Impact of erosion in the taluses of subtropical orchard terraces. *Agriculture, Ecosystems & Environment,* 107**,** 199-210.