



Hannah Nicola Grace Ritchie

Assessing the functionality of sand dams as a dryland water source
through an evaluation of water loss pathways

School of Water, Energy and Environment
Doctorate of Philosophy

PhD Water Sanitation and Hygiene
Academic Year: 2019 - 2024

Supervisor: Professor Ian Holman
Associate Supervisor: Dr Alison Parker
March 2024



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Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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Abstract

Between 1 - 2 billion people worldwide suffer from water scarcity, most of whom live in drylands. Irregular but intense rainfall have led to the proliferation of water harvesting. Sand dams, one such technique, comprise a concrete dam wall constructed across ephemeral rivers, which facilitate the accumulation of alluvium. Such dams can store and lose water to varying degrees, the extent of which is unclear.

This research therefore aimed to evaluate spatial and temporal water losses from sand dams in order to understand their storage potential and their contribution to water availability within the river channel and surrounding weathered basement aquifer. Through monitoring telemetered abstraction data and employing analytical modelling, this thesis explored variations in rates of water use and seepage from sand dams in Kenya. By being the first study to use 2D geophysics at sand dams, it improved the understanding of how sand dams interact with the surrounding hydrogeological environment.

Contrary to assumptions, geophysical inversions successfully showed that the trapped alluvium of sand dams typically overlies weathered basement material up to approximately 25 m in thickness, rather than impermeable bedrock. Alongside simulated flow rates, averaging 32.4 m³/day and empirical evidence, results highlight a partial recharge function performed by sand dams, primarily driven by lateral flow. Despite this, estimated groundwater volumes at full capacity, of up to 4,200 m³, were sufficient to meet community water needs throughout the dry seasons, in part due to recharge to the sand dams. This indicates the storage capabilities of the studied sites.

By identifying site and hydrogeological characteristics that may result in lower levels of seepage from the dams, and greater recharge to the dams, the findings aim to enhance site selection and dam construction, enabling more sand dams to better meet storage requirements. This will contribute to facilitating the implementation and scaling-up of sand dams in areas where they are physically suitable and appropriate to the specific needs of a community.

Keywords:

Kenya; Arid-Semi Arid Land (ASAL); Alluvial aquifer; Water Harvesting; Managed Aquifer Recharge (MAR); Water Security; Nature Based Solution (NBS); Ephemeral River; Abstraction; Seepage; Evaporation; Telemetry; Geophysics; Electrical Resistivity Tomography (ERT); Modelling.

Dedication

To Grandpa, for being my eternal source of inspiration and guiding light.

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I would like to thank my project partners, Sand Dams Worldwide (SDW) and Africa Sand Dam Foundation (ASDF). I thank SDW for partly funding the project, for providing data, and for meeting to discuss ideas and results. I especially thank Christine Whinney and Callum Sheehan from SDW for providing meaningful insights into my analysis. I am very grateful to ASDF for welcoming me so gracefully in Kenya and for the warmth shown, especially by Cornelius Kyalo, Andrew Musila, Boniface Mavindu, Jackline Naomi, and Mwanaid. Thank you for providing accommodation and food, driving me to sites, and for providing timely responses to my email requests for data and advice. I am grateful to the UK Engineering and Physical Science Research Council (EPSRC) for funding the majority of this research.

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I am very grateful to everyone I met and had the pleasure of working with in Kenya, especially Justus Nyangoka, Charles Mwangangi Muriuki, Paul Maina, and their families. Your friendship and guidance mean an awful lot to me. Without you, this research would not have been possible. Thank you for providing me with accommodation, transport, manpower, and laughter. I will definitely never forget you. I also owe a lot to the community members at the sand dam sites. Thank you for your insights, friendship, food, and laughter.

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Positionality Statement

I include this positionality statement as a declaration of my current understanding of who I am and how this may impact my work. I include it to be transparent about my identity and background so that you, as the reader, can know the perspective of the author. I am a British, white, female, early career researcher. Whilst my research is based in Kenya, I had never visited Kenya until 2022. My research is predominantly quantitative. However, my personal and social identities culminated in the privileged position that allowed me to conduct this research in the first place, impacted my access to information (likely both positively and negatively), and introduced bias into some of the results.

Whilst the framing of this thesis is water insecurity in specifically rural Kenya, I acknowledge and emphasise that water insecurity is not experienced by the majority of the Kenyan population. Whilst this may seem obvious to some, the stereotypes of talking about a single country in Africa, or more commonly the whole of Africa as though it is one homogenous place is far too common. The work focusses on sand dams, which are found across the continents of Africa, Asia, and North America. Sand dams in Makueni County, Kenya, were used as a case study, but the outputs generated from the research are more broadly relevant to worldwide water security challenges.

Dissemination of Research Findings

Peer Reviewed Papers:

Ritchie, H., Eisma, J. A., & Parker, A. (2021). Sand dams as a potential solution to rural water security in drylands: Existing Research and Future Opportunities. *Frontiers in Water*, 3, 651954. <https://doi.org/10.3389/frwa.2021.651954>

Ritchie, H., Holman, I., Parker, A., & Chan, J. (2023). Sand dam contributions to year-round water security monitored through telemetered handpump data. *Environmental Monitoring and Assessment*, 195(11). <https://doi.org/10.1007/s10661-023-11694-9>

Ritchie, H., Holman, I., Nyangoka, J., Bauman, P., Parker, A. Insights from Electrical Resistivity Tomography on the hydrogeological interaction between sand dams and the weathered basement aquifer (Under review. *Journal of Applied Geophysics*)

Ritchie, H., Holman, I., Parker, A. Evidence and drivers of seepage from sand dams: insights from empirical evidence and modelling. (Upcoming)

Conference Presentations:

Ritchie, H., Holman, I., Parker, A. Sand dam contributions to water security in Kenya monitored through hand pump abstraction. *Water & Environment Student Talks*. Vancouver, Canada. 8 - 10 June 2022

Ritchie, H., Holman, I., Parker, A. Sand dam contributions to water security in Kenya monitored through hand pump abstraction. *1st Water-WISER ERC Conference*. Loughborough University, England. 21 - 23 June 2022

Ritchie, H., Holman, I., Parker, A. Sand dams: The answer to dryland water insecurity? *21st AfWA International Congress and Exhibition and 7th FSMA Conference*. Abidjan, Cote D'Ivoire. 19 - 23 February 2023.

Ritchie, H., Shepherd, J., Garde, W., Nhlema, M, Scott, F., Bereziat, E., Okettayot Lobi, S., Cuscuna, L. WRM data collection, visualization, and management decision-making. *All Systems Connect International Symposium*. The Hague, Netherlands. 2 - 4 May 2023.

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List of Abbreviations

ASDF	Africa Sand Dan Foundation
bgl	Below ground level
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CURES	Cranfield University Research Ethics System
D_i	Depth from base of riverbed to top of unweathered bedrock
ERT	Electrical Resistivity Tomography
F	Constant calculated by Equation 3 for shallow river channels
GRACE	Gravity Recovery and Climate Experiment
GSM	Global System for Mobile Communication
H_w	Thickness of water saturated material in the riverbed (m)
IP	Induced Polarisation
I_s	Seepage rate (m^3/day)
K	Hydraulic conductivity (m/s)
MRS	Magnetic Resonance Soundings
MAR	Managed Aquifer Recharge
MODFLOW	Modular finite-difference flow model
NDMI	Normalised Difference Moisture Index
NDVI	Normalised Difference Vegetation Index
PET	Potential evapotranspiration
P/PET	Ratio of precipitation to potential evapotranspiration
RWH	Rainwater Harvesting
SDG	Sustainable Development Goals
SDW	Sand Dams Worldwide
SMS	Short Message Service
UNEP-WCMC	UN Environment Programme World Conservation Monitoring Centre
UNICEF	United Nations International Children's Emergency Fund
VES	Vertical Electrical Sounding
WaPOR	Water productivity through open access of remotely sensed derived data
WaSH	Water, Sanitation, and Hygiene
WDT	Water Point Data Transmitter
WHO	World Health Organisation

W_s	Width of riverbed at the surface (m)
ΔH	Vertical distance between water level elevation in the riverbed and weathered basement (m)

1 Introduction

1.1 Dryland water security

Between 1 - 2 billion people worldwide suffer from physical or economic water scarcity, most of whom live in drylands (Stringer et al., 2021). A country is classed as physically water scarce if it has $<1,000 \text{ m}^3/\text{capita}$ of annual renewable freshwater resources (World Bank, 2000) and economically water scarce if infrastructural, economical, and institutional factors limit water access (Ingram & Kessides, 1994; Rosa et al., 2020).

Drylands, comprising 41% of the Earth's land surface, are home to approximately 2 billion people, and are rich in biodiversity (Maestre et al., 2012; Rezende et al., 2016). However, high rates of water loss from evapotranspiration due to high temperatures and prolonged dry seasons results in arid conditions and severe water security challenges (Davies et al., 2016; Solowey et al., 2013). Drylands and associated water scarcity are found across six of the seven continents.

Africa, the world's second largest continent is home to almost one third of global drylands, where they account for approximately 43 and 50% of the land area and population respectively (Cervigni & Morris, 2015; Global Centre on Adaptation, 2021). Approximately 230 million people in Africa (15% of the population) face water scarcity (UN Economic Commission for Africa, 2000). Whilst groundwater is a critical water source across large swathes of the continent, there are disparities between storage and recharge patterns. Typically, there are high storage but low recharge sedimentary aquifers and low storage, but high recharge crystalline basement aquifers found across Africa (MacDonald et al., 2021) (Figure 1-1). An unequal distribution coupled with a general under exploitation of groundwater resources (UNICEF & WHO, 2015) in part contribute to approximately 21% of the population in Africa relying on unimproved or surface water sources (WHO & UNICEF, 2022). The majority of these people live in rural areas and require sustainable management techniques to improve the quality and quantity of their water supply (WHO & UNICEF, 2022). Improved infrastructure, a diversification of water sources and an accurate assessment of

water use are critical in order to meet Sustainable Development Goal (SDG) 6.1: “Universal and equitable access to safe and affordable drinking water for all” (UN, 2023).

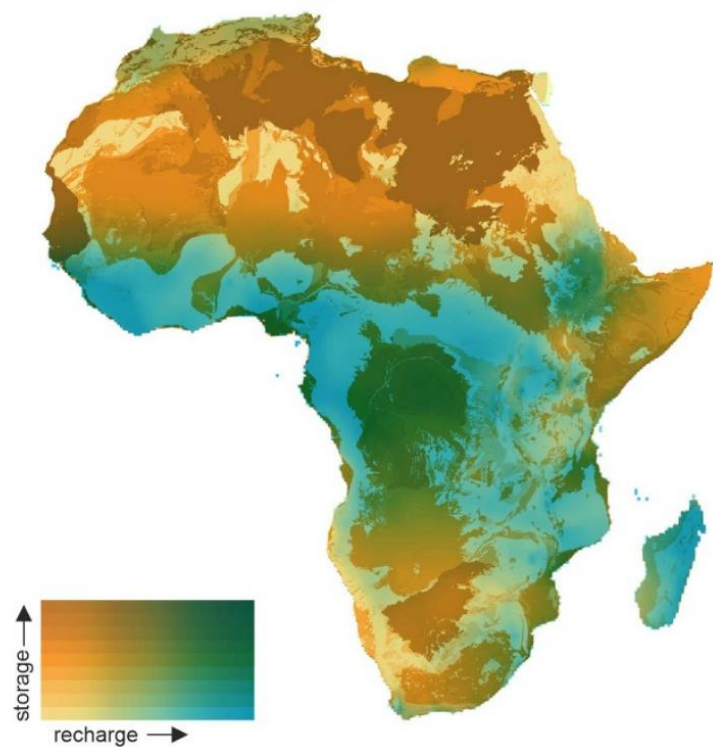


Figure 1-1: Recharge and groundwater storage across Africa (MacDonald et al., 2021) Reproduced with the permission of the British Geological Survey © UKRI [2024]. All Rights Reserved

1.2 Dryland water management techniques

The growing gap between supply and demand, poor access to or availability of groundwater resources in certain areas, and irregular but high intensity rainfall in drylands have led to the proliferation of alternative water management techniques, especially water harvesting structures (Ruffino, 2009). Water harvesting is defined by Beckers et al. (2012) as “the process of harnessing water for beneficial use with any kind of device or technique that collects, stores, and/or increases the availability of intermittent surface runoff and groundwater”. Water

harvesting is an ancient water management technique performed for millennia by individuals, communities, and governments across the world, with some of the earliest known infrastructure dating from 7000 BC in Mesopotamia (Baba et al., 2018). Water harvesting can provide a buffer against the effects of variable rainfall, helping to aid in managing dry periods more effectively. In some cases, however, the quantity of water collected may be insufficient to meet all domestic and livelihood water needs. Further, whilst they generally provide improved water quality compared to some other sources such as open ponds and rivers (Efe, 2006; Pinfold et al., 1993), they can still be a source of waterborne diseases (Chang et al., 2004). There are many different types of water harvesting techniques. They include those that collect and store water: swales and pervious pavements, and those that also increase water availability: rainwater harvesting (RWH) tanks, tankas, johads, and bhungroos (Jia et al., 2015; Owusu et al., 2017; Pfeil et al., 2018; Prabhu et al., 2012; Saxena, 2017).

Sand dams (Figure 1-2) are one such water harvesting technique. Sand dams, otherwise known as trap dams, sponge dams, or desert water tanks (Van Haveren, 2004) are simple, nature based, indigenous water management structures. They are small dams constructed across ephemeral rivers. Whilst similar to check dams, which contribute to groundwater recharge and river base flow, sand dams function as sediment-trapping devices, which is not the primary function of check dams (Dashora et al., 2018; Parimala Renganayaki & Elango, 2013; Parimala Renganayaki et al., 2015).

During the rainy season, alluvium, deposited from sediment laden run-off, accumulates behind the dam wall of a sand dam, in which water is stored. This water can be used in the dry season via scoop holes, shallow wells with handpumps, agricultural wells, and pools. The alluvium accumulates as a result of the dam itself (Figure 1-3). This is in comparison with sub-surface dams, which are constructed below ground level within pre-existing sediment, arresting the flow of water within the alluvial aquifer. Further, check dams, which hold back water, do not offer the benefits of trapping the water within sediment, and thus do

not provide the benefits of reduced evaporation and disease vectors offered by sand and sub-surface dams (Parimala Renganayaki & Elango, 2013).



Figure 1-2: Sand dam in Makueni County, Kenya. Dam wall consists of central spillway, 2.8 m in height, and wingwalls. Together they measure 23 m in length here. Trapped alluvium accumulated behind the dam wall extends 245 m upstream here (Ritchie, 2023).

Sand dams, being employed largely in rainfed agricultural areas facing perennial water shortages are predominantly intended for domestic and irrigation purposes (Maddrell & Neal, 2012; Neufeld et al., 2021; Villani et al., 2018). The water, however, has several uses, including for drinking, hygiene, laundry, cooking, cleaning, fishing, agriculture, livestock, and brick making (Maddrell & Neal, 2012; Parker et al., 2022).

Such structures are not novel. They are well known in the Middle East and Africa (Hut et al., 2008; Nilsson, 1988; Wipplinger, 1958). Accounts of similar structures exist from Sardinia in Roman times and from Mexico in the 18th Century (Cozens, 2017; Nilsson, 1988). A proliferation of sand dams in Kenya, in East Africa began in the second half of the 20th Century (Stengel, 1968).

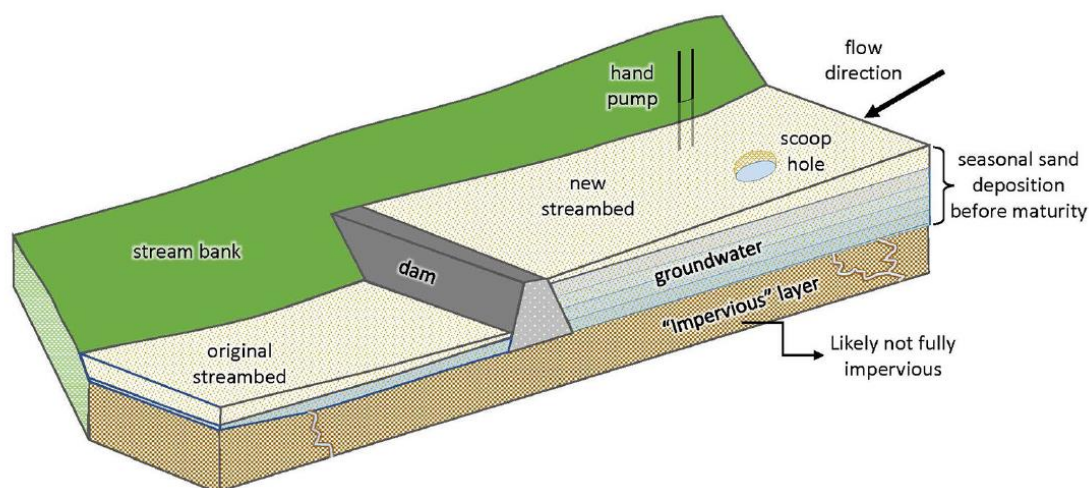


Figure 1-3: Schematic diagram of a sand dam holding back sand upstream of the dam wall (Ritchie et al., 2021)

1.3 Rural water supply

Over the past four decades, billions of dollars have been spent on providing and improving rural water supply in low and middle-income countries. Whilst community-based management schemes flourished in the late 20th century, a greater involvement of local private operators, ideas around community-management plus, and an increase in public-private partnerships have been seen in recent years (Hutchings et al., 2017; Lockwood & Smits, 2011).

Despite investment in innovative management schemes, water supply techniques, and smart technologies, many, especially rural communities, are not on track to meet SDG 6.1. Poor management and maintenance, and a lack of supply chains and financial support often result in the disruption of rural water supply (Lockwood & Smits, 2011; Mothetha et al., 2007). Many examples of successful rural water supply projects have relied on highly motivate communities often working in sustainable partnership with NGOs and government bodies (Lockwood & Smits, 2011). Sand dams benefit from being community driven, with some of the most successful sand dams being those close to and/or frequently visited and supported by local NGOs (Maddrell, 2018).

Sand dams can be used both where abstractable groundwater is and is not available. They may be able to augment the local groundwater supply through

interaction between alluvial and weathered basement aquifers (Hartley, 1997; Hut et al., 2008; Yifru et al., 2021). Whilst boreholes can usually provide a higher water yield, and will often be the preferred option if feasible, they have slightly higher initial costs, and much greater maintenance needs post-construction compared to sand dams (MacDonald & Davies, 2000; MacDonald & Calow, 2009). Requiring minimal maintenance post-construction, the sand dams themselves and respective abstraction via scoop holes do not require the same supply chains that traditional boreholes do. This is not the case, however, for the handpumps within the alluvial riverbanks, which do require maintenance (Ritchie et al., 2021).

With several NGOs working almost exclusively to promote and build sand dams, there is bountiful support within areas in which they operate. Being low cost and having been shown to often improve water availability for small communities, local and national governments in Kenya and beyond are starting to understand their potential benefits, choosing to increasingly invest in their construction.

1.4 Kenyan water security

The majority of Kenya is classified as dryland: ranging from arid and semi-arid to dry sub-humid (Figure 1-4). Favourable physical conditions and a high dependence on surface water (representing 92% of total available water resources), especially rivers and streams, have led to the largest worldwide concentration of sand dams in Kenya (Chepyegon & Kamiya, 2018; Maddrell, 2018). It is estimated that Kenya is home to >3,000 sand dams (Viducich, 2015), the majority of which are found in three main counties: Makueni, Kitui, and Machakos (Eisma & Merwade, 2021). This concentration is attributed to several factors. These include the hydraulic suitability of seasonal rivers with high coarse sediment load and a history of community adoption and utilisation of water harvesting techniques. Further, a strong presence of NGOs, government initiatives, and research here have provided a snowball effect, amplifying the adoption and implementation of sand dams through knowledge dissemination and funding support (Eisma & Merwade, 2021; Maddrell & Neal, 2012). These sand dams are typically located in areas of basement rocks.

Annual water demand in Kenya by 2030 is estimated to be around 6,700 million m³. This falls within the annual estimated safe water yield (from surface and groundwater combined) of approximately 8,500 million m³ (JacobsGIBB Ltd, 2003). Despite this, poor water management and low infrastructure investment mean that national water demand currently exceeds abstractable ground and surface water by approximately 4.8 million m³/day (JacobsGIBB Ltd, 2003). Water resource degradation, population pressure, and climate change are just a few of the further challenges that will increasingly face the water sector in Kenya and the rest of the world (Chepyegon & Kamiya, 2018).

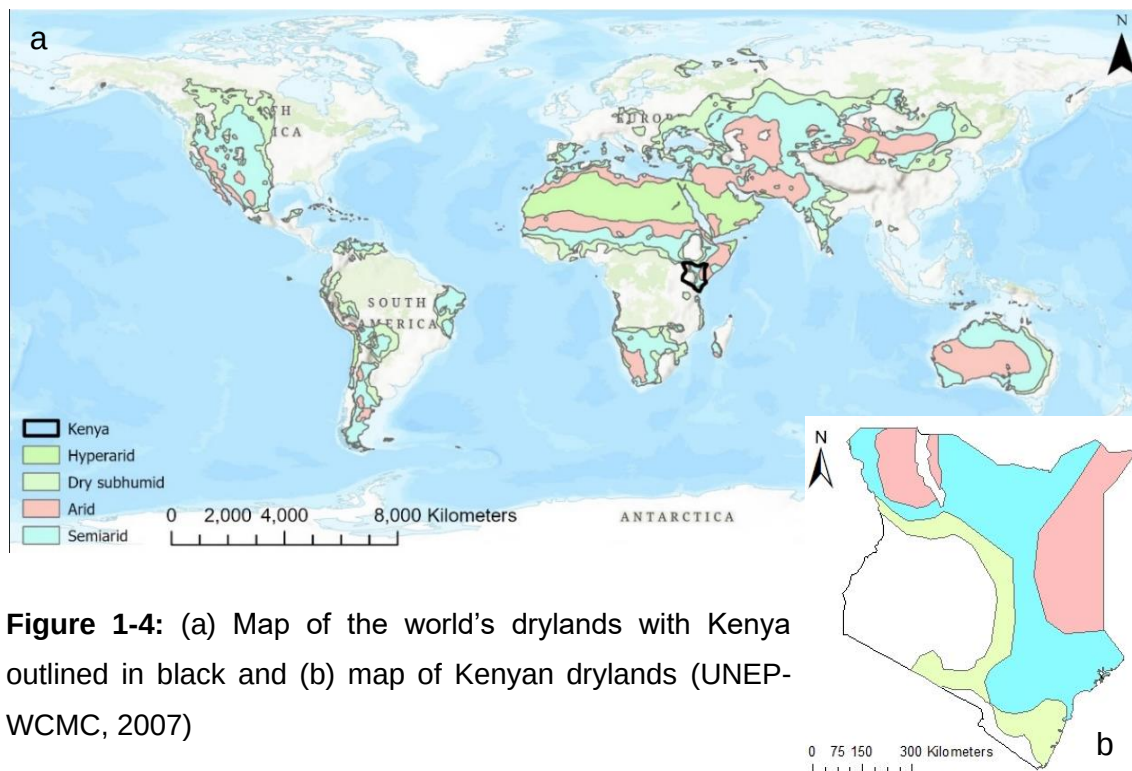


Figure 1-4: (a) Map of the world's drylands with Kenya outlined in black and (b) map of Kenyan drylands (UNEP-WCMC, 2007)

1.5 Sand dams: a dryland water management technique

1.5.1 The interaction of sand dams with the surrounding weathered basement aquifer

Sand dams are providing one potential solution to water insecurity in Kenya and other drylands. Many studies demonstrate the positive impacts that sand dams

can have on the growing threat of dryland water insecurity. These include increased water storage, reduced evaporation in comparison with surface water, and improved water quality and ecosystem health (Borst & Haas, 2006; de Bruijn and Rhebergen, 2006; Eisma & Merwade, 2020; Lasage et al., 2008; Manzi & Kuria, 2011; Maddrell et al., 2018; Neufeld et al., 2020; Pauw et al., 2008; Quinn et al., 2018a, b; Ryan & Elsner, 2016).

Further, sand dams have multiple benefits over traditional dams. Costing, on average between €6000 - 10,000, sand dams are more affordable than other larger dams (Ertsen & Hut, 2009; Lasage et al., 2008; Munyao et al., 2004; Trinchera et al., 2018; Tuinhof & Heederik, 2002). Further, they withhold on average only 3% of run-off, resulting in no water deficit downstream (Maddrell, 2018). Finally, intended for small scale water supply, sand dam construction is usually led by the community. This makes a dry season water source available to low-income communities, promoting strong and coherent community structures in the vicinity of the sand dam.

This section explores the pathways through which water can be lost from a sand dam. It aims to grasp the existing understanding of the extent to which sand dams interact with the surrounding weathered basement and atmosphere and whether they perform storage or recharge functions.

Sand dams can be sited to augment storage in alluvial rivers and/or to induce potential recharge in the local aquifer depending on the nature of the surrounding subsurface (Hartley, 1997). Construction of a sand dam is often initiated by community requests to NGOs and local governments, who wish to enhance water availability for immediate use (Maddrell, 2018). As such, the priority of sand dams is usually storage. In literature, sand dams are classified as runoff or rainwater harvesting structures (Maddrell, 2018; Yifru et al., 2021), artificial perched aquifers (Eisma & Merwade, 2020; Lasage et al., 2008; Manzi & Kuria, 2011), storage structures (Borst & Haas, 2006; Hoogmoed et al., 2007; Hut et al., 2008), or Managed Aquifer Recharge (MAR) structures (Quinn et al., 2019; Yifru et al., 2018). This suggests a degree of contention and a lack of coherent conceptualisation regarding their true hydrogeological functionality.

It appears unlikely that sand dams behave as isolated storage structures (Quinn et al., 2019). Water from sand dams has been measured, modelled, or hypothesised to be lost via multiple pathways. These include into the surrounding weathered basement aquifer through the riverbank or channel base; over, under, and around the dam wall; as abstraction; and as evaporation (Aerts et al., 2007; Borst & Haas, 2006; Eisma & Merwade, 2020; Hoogmoed et al., 2007; Hut et al., 2008; Jansen, 2007; Loon & Droogers, 2006; Maddrell, 2018; Quinn et al., 2019). The former three loss pathways may reduce water availability in the alluvium for immediate use but recharge the surrounding aquifer and provide usable pooled water downstream (Gijssbertsen, 2007; Parker et al., 2022).

Evaporation and interaction with the weathered basement via the riverbanks have been explored to an extent. Employing water balances, studies have found significant loss from evapotranspiration of up to 88% (Eisma & Merwade, 2020; Quinn et al., 2018b; Trincheria et al., 2015). Eisma & Merwade (2020) and Ndekezi et al. (2023) found evapotranspiration to be the largest contributor to loss at all and most studied sites respectively (both $n=3$), despite evaporation reduction being one of the main claimed benefits of sand dam construction. Whilst evaporation losses from the riverbed alluvium have been measured as minimal (Borst & Haas, 2006), both of these studies included evapotranspiration from the riverbanks. At the one site where Ndekezi et al. (2023) did not find evapotranspiration to be the largest contributor to loss, its contribution to total loss was only marginally (8%) smaller than seepage losses, which accounted for 52% of total loss. The lower and higher contribution of evapotranspiration and seepage respectively at this site may have been because of the slightly smaller estimated surface area and the slightly higher porosity of the alluvium respectively. Such findings suggest that the majority of loss is not beneficial for direct human use.

Remote sensing studies have used Normalised Difference Vegetation Index (NDVI) and Normalised Difference Moisture Index (NDMI) to assess the generally positive impact of sand dams on vegetation growth as a proxy for loss into the riverbanks (Demessie & Woldeyohannes, 2024; Eisma & Merwade, 2021;

Jansen, 2007; Manzi & Kuria, 2011; Neufeld et al., 2021; Ryan & Elsner, 2016). In addition to remote sensing, seepage into the weathered basement via riverbanks has also been explored or assumed within water balances (Borst & Haas, 2006; Eisma & Merwade, 2020; Ndekezi et al., 2023; Quinn et al., 2019) and subsurface models (El-Hames, 2012; Hoogmoed et al., 2007; Hut et al., 2008; Quilis et al., 2009; Yifru et al., 2020). Only Borst & Haas (2006), Ndekezi et al. (2023), Quinn et al. (2019) and Yifru et al. (2020), however, provide quantified values of lateral seepage and gains. Values of seepage provided by the former three are based on the residual of other components of a water balance, whilst values from Yifru et al. (2020) derive from a model set up in MODFLOW. No models have specifically focussed on quantifying both lateral (into the surrounding aquifer) and longitudinal (under and around the dam wall) seepage losses.

Whilst models have been used to explore how sand dams interact with the surrounding aquifer, they are generally based on one idealised sand dam or a catchment of multiple sites. As is always the case with modelling, some assumptions were made due to data scarcity (Borst & Haas, 2006; Loon & Droogers, 2006; Quinn et al., 2019). Borst & Haas (2006) for example, assumed that inflows from seepage from an upstream dam would be equal to outflows from seepage from the studied dam. They recognise that this will not be the case in reality. They also assume that abstraction remains constant year-round, which is very unlikely to be the case as sand dams are recognised to be particularly dominant as a water source in the dry season (Lasage et al., 2008; Maddrell & Neal, 2012; Neufeld et al., 2020; Strohschein, 2016). Further, specific yield is often assumed to be fairly high in most sand dam studies, with values of ≥ 0.3 regularly used. Dubreuil (2017), Quinn et al. (2019), Simon (2019), and Trincheria et al. (2018) however measured lower values in the field of 0.07 - 0.24. Only one study has assessed what impacts such seepage (Quinn et al., 2019). They found seepage to be most sensitive to the specific yield of the alluvium due its high impact on water storage.

Studies rarely consider loss under and around the dam wall. Those that do, have not quantified it, but have assumed it from observations of pooling. Neither do they usually consider the sub-vertical flow component of lateral seepage into the underlying weathered basement via the base of the river channel (Aerts et al., 2007). This is because the trapped alluvium is often assumed to directly overlie unweathered, impermeable bedrock or clay (Ertsen et al., 2005; Nissen-Petersen, 1997). This is cited as critical for prolonging storage (Gezahegne, 1986). A number of papers, however, suggest (but have not investigated) that the 'impermeable' layer is rarely, if ever, fully impermeable (Borst & Haas, 2006; Eisma et al., 2021; Gezahegne, 1986; Hut et al., 2008; Maddrell & Neal, 2012; Quinn et al., 2019), assuming construction on a fractured base or pre-existing alluvial aquifer. This would allow loss via seepage into the basement (Gijssbertsen, 2007).

Dryland ephemeral rivers and underlying aquifers have been found in hydraulic continuity in multiple studies. Focussed recharge can occur depending on the hydraulic conductivity of the riverbed and underlying material (Azevedo Toné et al., 2023; Carter & Alkali, 1996; Scanlon et al., 2006; Seddon et al., 2021; Zarate et al., 2021). According to Jaafar (2014), river channels in arid areas are characterised by high transmission losses. Azevedo Toné et al. (2023) measured water levels and flow rates and studied satellite images on the Jaguaribe River, Northeastern Brazil, an area predominantly composed of Precambrian crystalline basement. Whilst they found interaction between the river and underlying basement, losses for demand supply in the surrounding aquifer were usually insignificant. Seddon et al. (2021) and Zarate et al. (2021) further studied ephemeral interaction with the underlying crystalline bedrock of the Dodoma System in the Little Kinyasungwe Catchment in central Tanzania. The former studied groundwater recharge, rainfall, and ephemeral stream stage. They found stronger correlations between groundwater recharge and ephemeral streamflow than rainfall, indicating the importance of focussed recharge as a recharge mechanism here. The latter used Electrical Resistivity Tomography (ERT) and found that alluvial deposits can collect and store water that can recharge the underlying basement through fault zones and windows within clay layers.

Current knowledge on the nature of the material underlying the trapped alluvium of sand dams relies on limited Vertical Electrical Sounding (VES) surveys, piezometers, and augers. The invasive studies using augering extend to approximately only 1 m below the base of the trapped alluvium (Borst & Hass, 2006). Sixteen VES surveys were conducted by Hoogmoed et al. (2007) at one site in Kitui. They provide an initial, deeper (up to approximately 16 m bgl) insight into the nature of the subsurface directly beneath and up to 300 m either side of the riverbed. Unweathered bedrock was found to be only 1 m bgl beneath the riverbed at this site, but up to 16 m bgl towards the hillcrest.

Finally, no studies have collected data prior to sand dam construction to quantitatively inform on changes in water availability between pre- and post-construction and models incorporating seepage lack empirical validation.

1.5.2 Sand dam water supply capacity

Despite the benefits offered by sand dams, challenges also exist. These include the limited water supply capacity of some dams, the continued risk of evapotranspiration, and loss from seepage (Borst & Haas, 2006; Eisma & Merwade, 2020; Lasage et al., 2008; Loon & Droogers, 2006; Ngugi et al., 2020; Nissen-Petersen, 2010; Quinn et al., 2018b, 2019; Ryan & Elsner, 2016; Trinchera et al., 2015, 2018). Variations in water supply capacity between pre- and post-construction and between different sites will be explored in this section.

A limited number of qualitative studies provide insight into changes in water availability from pre- to post-construction. Pauw et al. (2008) found, from self-reported estimates from questionnaires that water usage had increased by 321% for households with access to a sand dam (n=98) compared to pre-dam construction. Increases were seen in all considered water use categories: domestic, agriculture, livestock, and brick making. They found a decrease in water use for agriculture of 3.1% but no change in the other water use categories within populations without a sand dam (n=39). Despite this change, domestic use was actually 7% lower in households using a sand dam compared to those without. The cause is reported to be unknown. Water used for agriculture on the other hand was 36% higher in households with a dam (463 compared to 294

L/day). This highlights the large positive influence that sand dams have specifically on agricultural water use. Lasage et al. (2008) similarly found a 50% increase in domestic water use and a 200% increase in agricultural water use post- (2005) compared to pre- (1995) construction. This change was noted in the Kiindu catchment in households using a sand dam (n=20). They found a decrease in water use in households in the Koma catchment, where no sand dams were constructed (n=19). Changes in water use in both studies relied on recall of up to 10 years, which could introduce a substantial risk of bias. Further, it is possible that other external factors may be influencing total water use between sand dam and control households, which were not accounted for in either study. No studies have assessed water storage or water use in real time in dryland riverbeds pre- compared to post-dam construction.

Estimates of maximum water volumes stored in sand dams vary substantially from 144 - 30,851 m³ (Eisma & Merwade., 2020; Hut et al., 2008; Lasage et al., 2015; Ndekezi et al., 2023; Neufeld et al., 2021; Quinn et al., 2019; Simon, 2019). Such differences derive from variable specific yields and sediment volume estimates due to differences in dam size and sediment storage capacity, as well as differences in methods of calculation and dam dimension estimates. Simon (2019), who studied 5 sites, estimated the highest water storage volumes. They calculated sediment volume from max. length * max. width * max. depth / 4. They used a specific yield of up to 0.3 and lengths and widths of up to 1,000 and 103 m respectively. This compares to the smallest estimates from Neufeld et al. (2021), who studied 97 sites. They estimated sediment volume using a geometric model consisting of a 2D polygon outlined by the dam structure. Width and depth were varied along the length of the trapped alluvium based on field measurements. Drawbacks (the estimated furthest upstream point of sediment accumulation) were estimated by the presence of a constriction in the channel such as rocks. Quantified dimensions are not provided but it is stated that long drawbacks were classed as >400 m. It is therefore assumed that sediment volumes were generally much smaller than in Simon (2019), in which none of the drawbacks were <400 m in length. The second study has a larger sample size and sediment volume estimates appear more accurate, suggesting that values in

the first study may be overestimated. Overall, the results still highlight the disparity in water availability between different sand dams and therefore their efficacy in improving water security.

1.5.3 Sand dam contribution to water security

Studies have assessed whether the water stored in sand dams can meet demands by qualitatively assessing water use through interviews and estimating water use from user numbers and minimum recommended water requirements (Borst & Haas., 2006; Jansen, 2007; Lasage et al., 2015; Ndekezi et al., 2023; Neufeld et al., 2021; Ngugi et al., 2020; Simon, 2019). Recall bias and changing user numbers introduces uncertainty regarding precise water needs, the adequacy of water volumes to meet these needs, and the duration of water sustainability from sand dams throughout the year. Abstraction volumes from sand dams have never been quantitatively assessed over a sustained period of time. Such insight would valuably contribute to understanding whether sand dams are being fully utilised and are able to meet water demands.

Some studies conclude that sand dams supply water to the local community throughout much of the dry season and exhibit a long-term positive impact on groundwater (Borst & Haas., 2006; Hut et al., 2008; Quilis et al., 2009; Jansen, 2007; Simon, 2019). Borst & Haas (2006) found that demand at their one studied site was being met, estimating from a water balance an availability of approximately 11m³/day compared to an average use of 8m³/day. This use derived from a population of 150 and an average household size of 7. A differentiation in water use is made between households that do and do not use water for irrigation (0.09 and 0.45 m³/day respectively). This again highlights the greater reliance on sand dams for agriculture (de Bruijn & Rhebergen, 2006). Jansen (2007), using a MATLAB-based model, similarly found that a water use of 8 m³/day (based on data from Borst & Haas (2006)) could be sustained from a modelled sand dam for 150 days (their approximated length of the long dry season). This reduced to only 140 days when seepage was accounted for in the model and was only 75 days when no dam was included in the model. Whilst this appears to indicate an unsubstantial contribution of seepage to loss, they only

included longitudinal loss under and around the dam wall and not into the weathered basement. Simon (2019), using interviews and water storage calculations, found that 100% of domestic water demand (15 L/person/day) was met at all four studied operational sites across a 5-month long dry season. Up to 280 households of 6 people/household were served. Combined domestic and livestock demand was met at only one site, with 58 - 77% coverage at the other three. This is because livestock demand estimates were, on average, 3.5 times greater than domestic demand. Livestock water demands, are, however, deemed less accurate than domestic estimates, partly due to pastoral immigration. They are based on the average number of animals and a daily average demand of 5 L/small animal and 20 - 30 L/large animal (WASH cluster-Somalia, 2018). Whilst the majority of water demands were met, interviews revealed that the well of one site is dry three months before the end of the dry season and that yield is very low in the last month of the dry season in the other three. Goats, which consume less water, are the most commonly kept ruminants in Makueni, followed by cattle (Kanui et al., 2016). There was, however, no indication of the distribution of livestock types in the study.

Other studies further find that storage cannot always meet demand, with a lot of water being lost to evapotranspiration and seepage from the sand reservoir rather than being utilised by the community (Jansen, 2007; Ndekezi et al., 2023; Neufeld et al., 2021; Ngugi et al., 2020; Trinchieria et al., 2015; Loon & Droogers, 2006). Such disparity indicates heterogeneity in water security benefits between different sites. Neufeld et al. (2021) found, through surveys, observations, and field measurements, that only 57% of studied sites (n=97) had enough water to provide four-months' worth of household water demand (15 L/person/day) to all beneficiaries (number not reported) if the sand dam was their sole water source. Trinchieria et al. (2015, 2018) undertook physical surveys and interviews and reported that only 33% of studied sites (n=30) had the capacity to supply water to one household during the entire dry season. This is assumed to be because of an absence of stored water by the end of the dry season at many sites. Neither household size nor household demand was reported. The poor supply capacity in this study is assumed largely to be due to high siltation, with silt accounting for

a median of 92% of sediments. Finally, Ndekezi et al. (2023) modelled a water balance at three sites. They found that total water storage after accounting for loss was highly variable (158.3 - 2,483.3 m³) and unable to meet estimated water demand across a 269 day period at any of the sites. This was, in part, due to a long modelled season, low water volume estimates at some sites, high water loss estimates, and high water demand estimates. Livestock water demand was based on head count estimates of 0.92 livestock/ha and a consumption of 50 L/livestock/day. Daily domestic demand was set at 20 L/person based on WHO recommendations (WHO, 2003). Agriculture demand was estimated at 10 m³/ha. Comparing bulk water demand with bulk water storage, and not reporting on or quantifying inflow into the system during the dry season, meant that the water demands were deemed not to be met.

Heterogeneity in site, hydrogeological, and climatic characteristics results in variable water security benefits offered by different sand dams. Despite this heterogeneity, successful sand dams have been shown to substantially increase water availability and use, whilst reducing traveling time for water collection (Aroka, 2010; de Bruijn & Rhebergen, 2006; Lasage et al., 2008; Maddrell, 2012; Pauw et al., 2008). Positive impacts, however, are not equally shared and depend on variables including hydrogeological conditions, abstraction method, and household location (Chan, 2019; Ertsen & Hut, 2009; Pauw et al., 2008). Whilst sand dams can increase water security and resilience, they may not be an inclusive solution for all (Ritchie et al., 2021).

1.5.4 Sand dams under climate change

Some limited analysis has been conducted as to the changing impact and behaviour of sand dams under climate change (Aerts et al., 2007; Lasage & Andela, 2011). This is an important consideration for any future dam construction and implementation of research findings, the results of which may change slightly with a changing climate. According to Aerts et al. (2007), the percentage of runoff captured by sand dams is predicted to increase, resulting in potential water shortages downstream, specifically between April - October. This is due to the

predicted decrease in overall runoff under climate change (Lasage & Andela, 2011).

Aerts et al. (2007), predict, with the expected reductions in water availability and higher water consumption, that the regularity of extreme water deficiency periods in Kenya will increase. Such insight highlights the importance of sand dams, which will only increase as rainfed agriculture potential decreases. It also has implications for likely increases in abstraction rates from sand dams in the future and potential conflict with downstream users. This means that even if a sand dam is storing enough water now to meet abstraction needs, this may not be the case in the future.

1.6 Research aim and objectives

The above research demonstrates that there is contention over the storage and recharge functions of sand dams and their ability to meet water demands. Many gaps remain in our understanding of sand dam hydrology and the opportunities that sand dams present for increased water security. From a literature review on sand dams during this thesis, it was recognised that an extensive field study to examine the spatial and temporal extent of groundwater impact that results from added storage in a sand dam is needed. If sand dams do significantly recharge the surrounding local groundwater table, such a study would explain the dynamics of the recharge process and provide insights into how sand dams function within their local ecosystem. Furthermore, quantifying abstraction and estimating water volumes to understand whether demands are being met is crucial to understanding the impact that sand dams have on water security.

The aim of this thesis is therefore “To evaluate spatial and temporal water losses from sand dams in order to understand their storage potential and their contribution to water availability within the river channel and surrounding weathered basement aquifer.”

The aim of this thesis is to be achieved through the following three objectives:

- To understand the contribution that sand dams make to the water security of dam users and how this varies spatially and temporally.

- To evaluate and contribute to the current conceptualisation of a sand dam within the surrounding weathered basement aquifer.
- To understand the interaction between sand dams and the surrounding weathered basement aquifer by evaluating seepage between the two and assessing the controls on the magnitude of this seepage.

By addressing this aim and these objectives, this thesis will add to current knowledge on the water supply capabilities of sand dams. By understanding what impacts seepage, the research will be useful for informing site selection and construction in order to maximise storage or recharge depending on the intended purpose of each site. It will indicate the abstraction patterns of current sites and what may influence such patterns, thus helping to understand and influence water use behaviour where appropriate. Finally, the research will highlight the benefits and limitations of sand dams in different locations, assisting funding applications and consequent construction where they are physically suitable and appropriate to the specific needs of a community.

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2 Study area

2.1 Geographic location

The study is located in Southeastern Kenya, predominantly in Makueni County (Figure 2-1). The area is part of the weathered basement complex area of the Athi catchment basin. Makueni County covers an area of 8,035 km² and lies between latitudes 1°35' and 3°00' South and longitudes 37°10' and 38°30' East, approximately 200 km South of Nairobi (Makueni County, 2013). Based on analysis of a recently compiled sand dam data base (Eisma et al., 2024, in press), the density of sand dams in Makueni is approximately 0.04 sand dams/km² (approximately n=340).

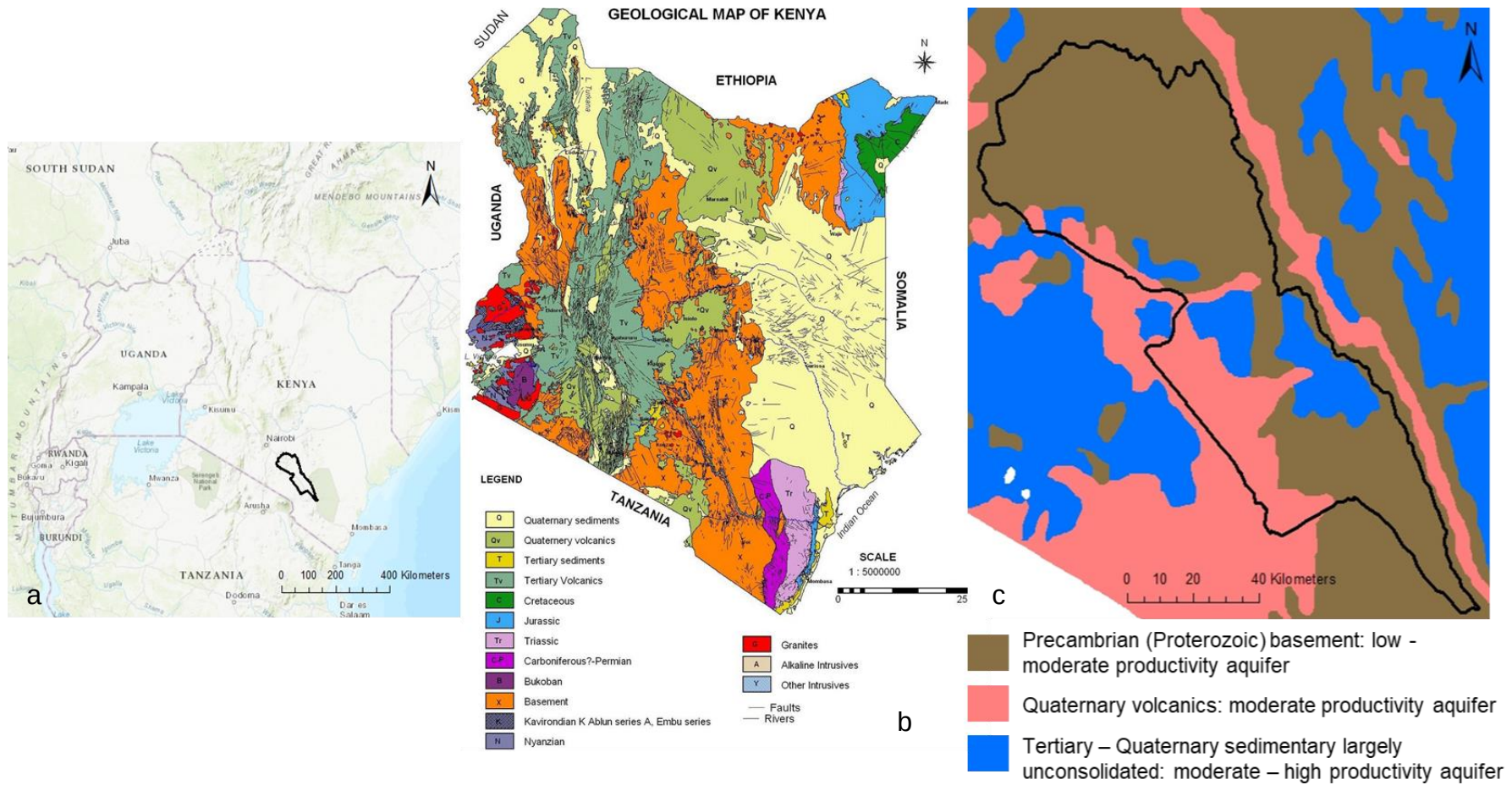


Figure 2-1: (a) Map of Kenya, (b) geological map of Kenya (Nyakinye, 2022), and (c) geological and hydrogeological map of Makueni County, Southeast Kenya indicating aquifer productivity. Reproduced with the permission of the British Geological Survey © UKRI [2024]. All Rights Reserved

2.2 Physiography and climate

The county's terrain is generally low-lying grassland from 600 m above sea level in Tsavo at the southern end of the county. This area has potential for livestock production, bee keeping, and horticulture production along the river basins. The northern part of the county is hilly with the potential for crop production, dairy, horticulture, and coffee production (Makueni County, 2013).

The county experiences two rainy seasons: approximately March - May (long) and October - December (short), separated by two dry seasons: June - September (long) and January - February (short) (Camberlin & Wairoto, 1997; Musyimi et al., 2023; Nganyi, 2009). Average rainfall ranges between 800 - 1200 and 200 - 900 mm/year for upper and lower zones respectively (Makueni County, 2013). The short rains are typically more evenly distributed, reliable and thus more effective than the long rains, with approximately 60% of annual rainfall received during the former period (Gichuki, 2000). Average annual temperature is 22.6 °C and potential evapotranspiration (PET) is high, with estimates ranging from 899±49.6 - 1,274±76.3 mm/year (Musyimi et al., 2020). According to the Aridity index, the county belongs to the semi-arid and dry sub-humid regions ($0.2 < P/PET < 0.65$) (UNEP-WCMC, 2007). Temperature and potential evapotranspiration are predicted to rise with climate change, the former by approximately 3 °C (Aerts et al., 2007). Combined with a general decrease in precipitation recorded across drylands in recent years (Daramola & Xu, 2022), this will likely exacerbate water insecurity in drylands and put increased pressure on limited water resources.

2.3 Population and water use

Makueni County has a population of approximately 1,090,000 (Ministry of Water Sanitation and Irrigation, 2024), with an annual growth rate of 1.4% (Kenya National Bureau of Statistics, 2019). The population is concentrated in rural localities (92%) (Brinkhoff, 2023), whilst the urban population is concentrated into six main towns (Republic of Kenya et al., 2023). Small-scale subsistence agriculture is the dominant socio-economic activity. Poverty rate is approximately

61%, being much higher in rural (67%), compared to urban (33%) populations (Nutrition International, 2019).

Despite reasonable rainfall, especially in the north, both high evapotranspiration and runoff lead to water deficits. According to Augustine et al. (2014) the average person in Makueni uses 19.6 $\pm$ 0.3 L of water per day with only 36% of the population having access to improved sources of water (Government of Makueni County, 2013). The major sources of water in the county are seasonal rivers (mainly Athi River and its tributaries), boreholes, earth dams, sand dams, and limited shallow wells and roof catchments. Water production is estimated at 14,489.9 m³/day compared to a demand of 40,794.4 m³/day (Government of Makueni County, 2019).

Water scarcity is exacerbated by over-abstraction, catchment degradation, climate change, unsustainable sand exploitation, pollution, poor regulation, and inadequate storage infrastructure (Government of Makueni County, 2019). Heavy metal pollution and pesticide residue, for example, have been reported in the Athi River (Gevera et al., 2020). Further, groundwater aquifers, whilst limited, are underutilised due to limited technological exploration and research and development (Government of Makueni County, 2019). Under climate change, net water availability is projected to decrease by approximately 1% from November - March and 34% from April - October (Aerts et al., 2007).

2.4 Geology

Kenyan geology is generally grouped into five successions: Archean, Proterozoic, Palaeozoic/Mesozoic sediments, Tertiary/Quaternary volcanics, and Tertiary/Quaternary sediments (Nyakinye, 2022) (Figure 2-1b).

Large parts of the northern and eastern areas of Makueni are underlain by low porosity, intensely folded Precambrian (Proterozoic) crystalline basement rocks. These consist of predominantly granitoid and biotite gneisses, belonging to the Kasigau series of the Mozambique Belt (Gevera et al., 2019) (Figure 2-1c). These rocks are permeable only when weathered and fractured (Ng'anga et al., 2018). The southern part of the county is underlain by basement rocks, which are

overlain by Tertiary and Pleistocene (Quaternary) volcanics and alluvial sediments (Dodson, 1953; Gevera et al., 2020) (Figure 2-1c). The rocks are generally orientated north - south (Ng'ang'a et al., 2015).

The rocks are weathered to varying degrees. The granitoid gneisses are more resistant to weathering and erosion than the other formations, and consequently form the majority of the hills in the area. The gneiss is dominated by biotite mica (in biotite gneiss), muscovite mica (in granitoid gneiss), amphibole, quartz, and potassium feldspar, which are sometimes concentrated into pegmatite veins. Locally, quartzites occur between the gneiss. Localised pygmatic folding in the gneiss indicates very high grade metamorphic conditions (Panchuk, 2019).

2.5 Soils

Soils in Makueni County are dominated by Rhodic ferralsols, Chromic Cambisols, Eutric Vertisols, Haplic Lixisols, and Chromic Luvisols, all of which are relatively clay rich (Batjes & Gicheru, 2004; Mwikali, 2023). Alluvial soils derive from the alluvial deposits. Amphibolites, rich in ferromagnesian minerals result in red clay soils, whilst gneiss typically gives rise to coarse soils (granitoid gneiss) and soils of variable textures (banded and biotite gneiss) (Muchenà, 1975).

2.6 Hydrogeology

Aquifers in Makueni are predominantly found within paleo-weathered horizons, contact zones, and joints within the deeper metamorphic basement, shallower volcanic rocks, and unconsolidated sediments (Dodson, 1953; Gevera et al., 2020) (Figure 2-1c). Several springs formed at the contact zones between the metamorphic and volcanic rocks provide domestic water to some of the larger towns (Gevera et al., 2020). The groundwater potential of the volcanic rocks, although highly variable, can be substantial (MacDonald & Calow, 2009). The porosity and permeability of unaltered pyroclastic rocks, for example, are similar to those of poorly sorted sediments, whilst basaltic rocks typically form very productive aquifers (Ng'an'ga et al., 2018). The unconsolidated sediments form some of the most productive aquifers (MacDonald & Calow, 2009).

Overall, the Precambrian basement rocks form low - moderate productivity aquifers (Gevera et al., 2020; Wright & Burgess, 1992) (Figure 2-1c). Crystalline basement rocks are naturally impervious, with negligible quantities of groundwater. They can, however, develop secondary porosity as a result of weathering under adverse climatic conditions (Anudu et al., 2014; Ng'ang'a et al., 2015). This results in a weathered profile (Bianchi et al., 2020; Wright & Burgess, 1992).

In regions of moderate - high annual rainfall (>600 mm/year), the water table typically occurs at shallow depth (<10/15 m bgl) in the upper saprolite (Wright & Burgess, 1992). In topographic highs and along channels of ephemeral rivers, bedrock may outcrop, therefore resulting in no or only a thin weathering profile (Zarate et al., 2021). Both primary porosity in the regolith and secondary porosity in the crystalline bedrock provide conditions for groundwater storage (Gevera et al., 2020; Wright & Burgess, 1992), although storage is derived largely from the former (Wright & Burgess, 1992).

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3 Methodological approach

The research strategy must be appropriate for the intended research objectives. Since this research aims to identify the extent to which losses from sand dams affect their contribution to water security, a multi-case study approach was considered most appropriate. This approach provides a granular understanding of specific contexts and allows differences between sites to be explored.

Due to an absence of research on new sand dams, new sites under-construction were selected to be studied. Previous research shows that sand dams are highly variable in their behaviour. It was therefore deemed important that more than one site was studied. Consequentially, three new and three mature sites were selected for the fieldwork component of this thesis, from which comparisons and changes over time could be assessed. Two field studies were undertaken: in February - March 2022 and 2023. Analysis of a large secondary data set of telemetered abstraction data, geophysical surveys, empirical data collection, and analytical modelling were the four main methodological approaches used in this thesis. The methods are described in more detail in each respective chapter.

The secondary data set was provided by project partners: Sand Dams Worldwide (SDW) and Africa Sand Dam Foundation (ASDF). In 2019, SDW and ASDF installed Water Point Data Transmitters (WDT) on the handpumps at 30 different sand dams. Working in collaboration with SDW, abstraction patterns from sand dams was identified as a valuable knowledge gap which needed to be filled. As Covid-19 travel restrictions meant that fieldwork was not possible, the analysis of this secondary data set comprised the first part of this thesis. Hourly abstraction data from 26 of the 30 sites were analysed across 31 months in order to understand how and why abstraction may vary seasonally and spatially. Such a long term analysis on handpump abstraction from sand dams had not been previously conducted. The analysis therefore provided valuable insight into the understanding of how sand dams contribute to water security.

Geophysical surveys using ERT were undertaken at six sand dams. Surveys were conducted at mature sites during the first field visit and at new sites during both field visits to assess change between pre- and post-construction. The nature

of the subsurface underlying sand dams has been limited to very minimal VES surveys, augers, and geological maps until now. 2D geophysical surveys had never been conducted at sand dam sites. This limits the conceptual understanding of how sand dams behave in their wider context. This is an important knowledge gap to fill in order for sand dams to be better sited, and for their holistic benefits and changes in storage to be better understood. Geophysical methods are generally employed to measure differences in the physical properties of the subsurface. They allow structures usually hidden from view to be imaged in a non-invasive and cheaper manner than through boreholes (Valenta, 2015). ERT depends on contrasts in electrical resistivity between subsurface materials (US Department of the Interior Bureau of Reclamation, 2001). It was chosen over other geophysical methods due to its common use and merit in groundwater studies due to its sensitivity to both lithology and water content, and its 2D capabilities (Ebong et al., 2021; Kumar et al., 2016a; Saad et al., 2012). The purpose of the surveys was to assess areas of saturation in and around the sand dams and the composition of the underlying weathered basement to understand seepage pathways. Being the first 2D geophysical study at sand dam sites, this investigation was very useful in adding to the limited knowledge of how sand dams interact with their surroundings.

Seepage was analytically modelled at the same six sand dams using Darcys Law and a version of the resistance equation, alongside evaporation and abstraction. The aim of this part of the thesis was to assess the temporal impact of different loss pathways on water storage. The model was calibrated against water level elevations by varying the hydraulic conductivity and specific yield at each site using the sum of squared differences. As water level elevations were collected at only one point in time (mid-way through the modelled period during fieldwork in 2023), modelling provided the best option for meeting this aim. Further, by modelling each site, telemetered abstraction data could be integrated into each site to assess whether the estimated water storage could meet dry season water needs. Using a water balance of inflows and outflows, the change in storage and subsequent change in head were calculated over time. This method enabled questions on water storage and seepage to be answered. It provided a simple,

user-friendly interface, making it accessible to sand dam practitioners and academics for future use. A sensitivity analysis was undertaken in order to assess the sensitivity of lateral and longitudinal seepage to different site, hydrogeological, climatic, and human parameters. With no sand dam models focussed on quantifying both lateral and longitudinal seepage, this thesis filled an important gap – providing valuable insight into water security and seepage patterns at sand dams.

Finally, empirical evidence, suggestive of potential seepage, including pooling, vegetation health and density, and material underlying the dam wall was collected at each of the six sites. This method was used in order to improve confidence in the analytical modelling. No studies which model seepage from sand dams have augmented this with empirical evidence. It was therefore deemed useful to provide an initial insight into how empirical evidence can be used to assess different sand dam behaviours. It is a simple and inexpensive method which can be employed when other methods may be inaccessible. Indicators used to assess evidence of potential seepage were scored from 1 - 4, increasing in likelihood of seepage. Each indicator was scored at each site and each site was ranked from least to most evidence of seepage (1 - 6). The scores were analysed to assess differences in seepage between sites. Such a framework for collecting empirical evidence provided a simple way of assessing seepage. It can be used and added to in the future to understand seepage from other sites.

Figure 3-1 outlines the methodological approach taken in the thesis.

3.1 Thesis structure

The thesis is structured into three introduction chapters, three chapters structured in the format of journal articles, and a discussion and conclusion chapter (Table 3-1).

Table 3-1: Overview of thesis structure

Chapter	Overview
One	Introduction to and gaps in previous literature and how this thesis aims to address current research gaps
Two	Study area
Three	Methodological approach
Four	Based on Ritchie et al. (2023). An analysis of handpump abstraction patterns at sand dams to explore temporal and spatial patterns of water use
Five	Based on paper two (under review). Examines how sand dams interact with their surrounding weathered basement
Six	Based on paper three (in preparation). Examines how seepage from sand dams varies spatially and temporally, what factors impact seepage, and whether storage is sufficient to meet water demands
Seven	Discussion of the research findings and conclusions of the study, highlighting impact, contributions, novelty, limitations, and recommendations
Eight	Conclusion of the research findings

A literature review was published alongside this thesis. It is included in Appendix B. The paper was the first comprehensive literature review on sand dams. It is not included as a chapter in this thesis as it was written in equal collaboration with a second author and much of the self-written content is not directly relevant for the content of this thesis. The published paper version of Chapter 4 is included in Appendix C.

Table 3-2 outlines the author contributions to the three papers related to Chapters 4-6.

Table 3-2.: Author contribution to each paper

Paper	Author contribution
One	Hannah Ritchie: Conceptualisation, Software, Formal analysis, Investigation, Data curation, Writing – Original Draft and Visualisation. Ian Holman: Methodology, Supervision, Writing – Reviewing and Editing. Alison Parker: Conceptualisation, Methodology, Supervision, Writing – Reviewing and Editing. Joanna Chan: Writing – Reviewing and Editing.
Two	Hannah Ritchie: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft and review and editing, Visualisation, Project administration. Ian Holman: Conceptualisation, Methodology, Writing – Review and Editing, Supervision. Justus Nyangoka: Investigation, Resources. Paul Bauman: Validation, Writing – review and editing. Alison Parker: Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition.
Three	Hannah Ritchie: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft and review and editing, Visualisation, Project administration. Ian Holman: Conceptualisation, Methodology, Writing – Review and Editing, Supervision. Alison Parker: Conceptualisation, Methodology, Writing – Review and Editing, Supervision, Funding acquisition.

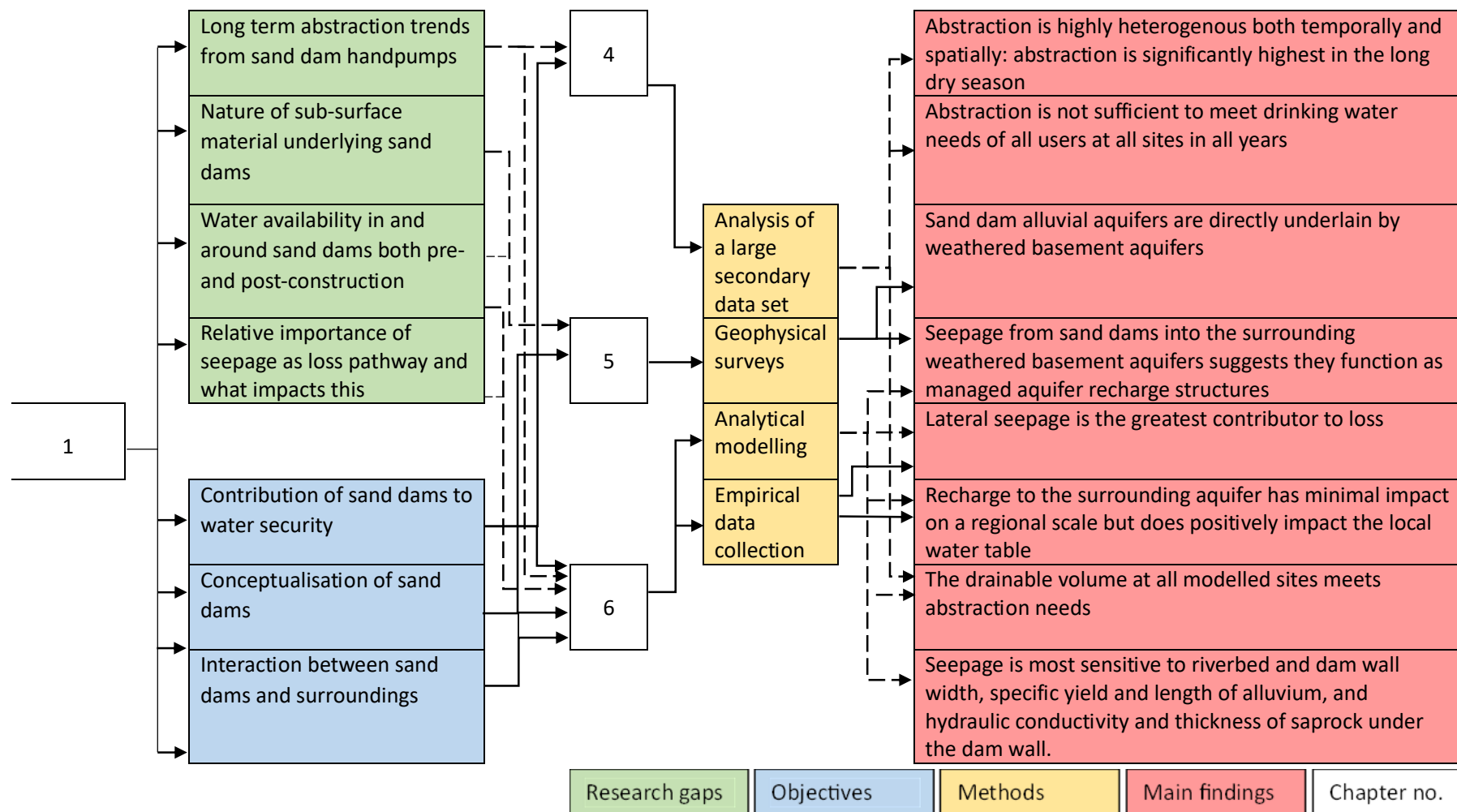


Figure 3-1: Framework detailing the contribution of each paper to the aim of the thesis. Solid and dashed lines are used for clarity.

3.2 References

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4 Sand dam contributions to year-round water security monitored through telemetered handpump data

4.1 Abstract

Sand dams are a form of rainwater harvesting, prolific in Arid and Semi-Arid lands. Water is provided partly via handpumps, which, as the only improved method of abstraction from sand dams, are important for drinking water security. Accelerometers and cellular transmitters were fitted to 30 sand dam handpumps by SDW and ASDF in 2019 to monitor the use and reliability of the handpumps by recording hourly water volume abstracted. Data from April 2019 - October 2021 for 26 of these sites, alongside qualitative data were analysed. Each handpump's contribution to year-round water security was explored, focusing on the long dry season when water supply from other sources is compromised.

Abstraction was over 30 times higher in the long dry season than in any other season, and at sites with higher recorded salinity values of the stored water, higher livestock use, and larger dam wall area. At 21 wells, abstraction was still being recorded at the end of at least one long dry season. High spatial and temporal heterogeneity between pumps and seasons, however, mean that not all sand dams may deliver reliable water supply year-round. Quantifying the contribution that sand dams make to water security is crucial for understanding their resilience against a changing climate and can aid decision makers when choosing the most appropriate water management technique. Knowledge of temporal and site heterogeneity in abstraction can inform when other water sources need increasing and can help with sand dam design optimisation. Overall, the results indicate the positive contribution that sand dams make to year-round water security through the water that is abstracted through handpumps.

4.2 Introduction

Drylands, or arid regions, face severe threats to water security, resulting in a deficit between supply and demand (Davies et al., 2016). As one of the most

sensitive areas to climate change (Huang et al., 2017), challenges related to water supply in drylands are increasing (Lian et al., 2021), meaning resilient, holistic approaches to water management are crucial. One such technique, popular in certain dryland settings, is sand dams.

Sand dams are predominantly found in Eastern and Southern Africa, India, and Brazil (Nilsson 1988). The water is used for domestic consumption, agriculture, livestock, and other water consuming projects such as brickmaking (Beswetherick et al., 2018; Cruickshank & Grover, 2012; Lasage et al., 2008; Parker et al., 2022; Pauw et al., 2008; Tuinhof & Heederik, 2002). The needs of individuals using a sand dam vary, but in general the dams must rarely provide for entire year-round water needs, with other sources such as boreholes, RWH tanks, kiosks, surface water, springs, and piped water supply also being used (Lasage et al., 2013; Neufeld et al., 2020; Strohschein, 2016). Whilst people rely more on RWH tanks in the rainy season (Adekalu et al., 2002; Boelee et al., 2013; Elliott et al., 2017; Özdemir et al., 2011; Shaheed et al., 2014), sand dams can be a useful source of water in the dry season when other sources run low or are unavailable (Maddrell & Neal, 2012; Neufeld et al., 2020; Strohschein, 2016). Water is abstracted from sand dams using handpumps, agricultural wells, pooled water, and scoop holes, with the latter cited to be present at almost 50% of sites studied by Neufeld et al. (2021) (N = 97), compared to handpumps, which were present at around only 16%.

Sand dams are most common in Kenya, where surface and unimproved water sources are used by 19 and 9% of people, respectively. Use of such sources endangers drinking water quality and future water security (WHO & UNICEF, 2022). However, the prevalence of streams and rivers with high coarse, suspended sediment loads offers opportunities for sand dam construction here (Hut et al., 2008; Mutati et al., 2018; Viducich, 2015).

There is uncertainty around the contribution that sand dams make to year-round water security. Ngugi et al. (2020), Loon & Droogers (2006), and Trincheria et al. (2015) found that many dams do not have the capacity to support water needs throughout the entire long dry season in Kenya. The former two studies are

located in the Tiva catchment (in the west of Kitui), whilst the latter is located in Makueni. Through surveys, Ngugi et al. (2020) found that 57 and 64% of 116 dams did not have water by the end of the short and long dry seasons respectively. Trincheria et al. (2015) found that 67% of 30 dams did not supply water to even one household during the entire dry season. From modelling, Loon & Droogers (2006) found an unmet demand from July - September. Borst & Haas (2006), Quilis et al. (2009), and Hanson & Nilsson (1986) cite the opposite. The former two studies are in the Kiindu catchment (a small catchment near Kitui town (Ertsen & Ngugi, 2021)), whilst the latter is based in the Hararghe region of Ethiopia. Hanson & Nilsson (1986) and Quilis et al. (2009) cite, from measurements and modelling respectively, that the dams are full several months after the end of the rainy season and can effectively increase water availability throughout the dry season. Borst & Haas (2006) found from a water balance of a single site that 11 m³ is now available per day in the study area from March - October, compared to 2 m³ before dam construction. Given the geographical similarity between most of the studies, location is not assumed to be the cause of differences in water availability. Further, there is no distinct difference in findings between modelling and fieldwork-based studies. No studies have specifically quantified annual water abstraction from sand dam handpumps from long-term monitoring, instead using modelling and qualitative methods. There is therefore uncertainty around the usefulness and financial viability of sand dams as an improved water source.

Quantifying the volume of water abstracted from sand dams via handpumps is key to understanding sand dam's contribution to water security, and their potential resilience and sustainability against a changing climate. Whilst abstraction volumes may be linked to storage, other variables, including convenience, quality, and the use of other sources can impact abstraction. It is recognised that handpumps are the only improved method of abstraction from sand dams. Due to the important health implications of such a supply, this study seeks to understand the contribution that sand dams make to year-round water security by specifically studying abstraction patterns from telemetered handpump data. The study combines data from interviews and empirical observations to assess

what may be impacting these patterns. The study is the first of its kind at sand dam sites to use long-term abstraction data, which avoids reliance on recall and assumptions made in modelling, and which spans a continuous 31 months rather than providing a snapshot in time. It is hypothesised that sand dams improve a community's year-round water security by sustaining water availability in the dry season. Proving or disproving this is important for understanding sand dam's level of use, acceptance, and cost efficiency. It will help to inform future water management interventions and to ensure that users are serviced with an improved supply throughout the year.

4.3 Material and Methods

4.3.1 Study Context

The study location was rural areas of the Makueni and Southern Machakos Counties, in Southeast Kenya (Figure 4-1), being chosen due to large investments in sand dam construction here. This region is characterised by four seasons, with an average annual rainfall from 1981 - 2021 across the 26 sites of 286 and 375 mm in the long and short rainy seasons respectively (661 mm in total) (CHIRPS, 2021). Some but minimal rainfall occurs during the dry seasons.

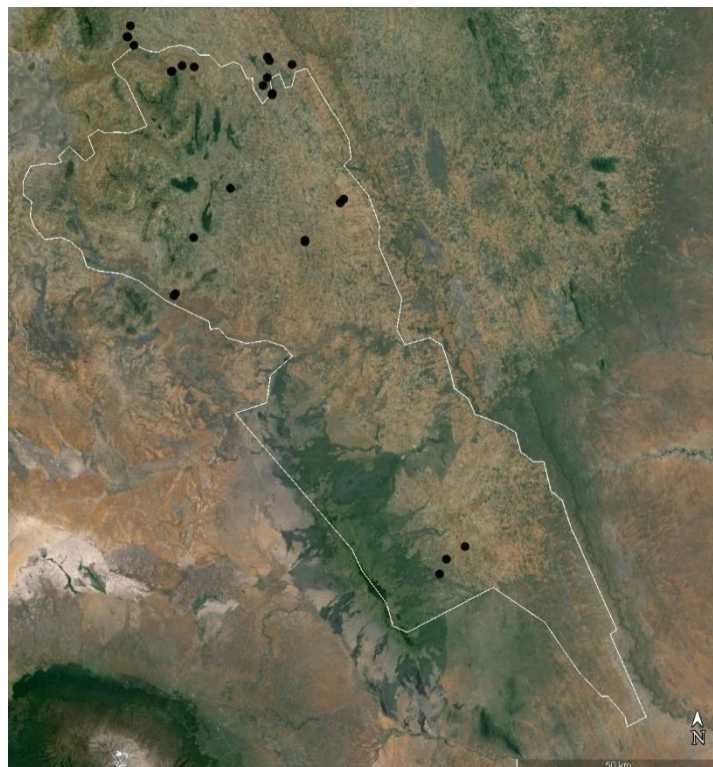


Figure 4-1: Outlined map of Makueni County, Southeast Kenya, and locations of the 26 study sites in Makueni and Southern Machakos Counties (Google Earth Pro, 2024)

4.3.2 Data sources

To quantify the contribution that sand dam handpumps make to year-round water security, three secondary data sets were used: telemetered hourly abstraction data, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall data, and site and behavioural characteristics provided by interview and empirical data.

The handles of 30 sand dam handpumps at 30 different sites were fitted with a WDT. The WDT consists of an integrated circuit based accelerometer, a microprocessor, and a Global System for Mobile Communications (GSM) modem (Thomson et al., 2012). The accelerometer measures the movement of the handles by sensing movement in X, Y, and Z planes to produce three analogue outputs proportional to the acceleration sensed along that axis. The microprocessor then takes the acceleration data in order to calculate pump handle tilt angle, which is monitored to produce a count of the number of strokes the pump handle has moved over a given time. The relationship between stroke length and number of strokes was used to estimate the volume of water abstracted. This calibration was performed by the developers of the WDTs on three handpumps in Lusaka, Zambia. No independent daily checks to calibrate recorded and actual abstraction were made specifically at any sand dam sites.

The data is then transmitted as a Short Message Service (SMS) via the GSM modem (Thomson et al., 2012). Thomson et al. (2019) previously calculated that the estimated volume abstracted (derived from the conversion of pump handle movements from the WTD) gives a +/- 15% accuracy against measured volume abstracted in the field.

Each site fitted with a transmitter was selected due to (1) a strong cellular network signal so that the accelerometers can transmit data (which are converted to abstraction volume) through the mobile network and (2) the handpumps being used daily in order to provide continuous data (Chan, 2019). ASDF visited each site to verify daily usage prior to transmitter installation. Some areas with high

usage had no network coverage, meaning that some sites with lower daily usage with network coverage were selected. 26 of these handpumps were selected for this study based on data availability and continuity. The data spans from April 2019 - October 2021.

CHIRPS data, a 35+ year quasi global rainfall data set was used to assess rainfall levels at the 26 dams. CHIRPS combines data from models, real-time observing meteorological stations, and 0.05° (5 km) resolution infra-red satellite data to estimate daily precipitation (Funk et al., 2015). Mulungu & Mukama (2023) evaluated the accuracy of CHIRPS. They found it to correlate well with ground rainfall observations on a monthly timescale, but less well on a daily scale, with Pearson correlation coefficients of $r>0.7$ and $r>0.5$ respectively. Although CHIRPS data is less accurate in dry than moist conditions, with light precipitation events found to be underestimated and heavy precipitation events overestimated, it has been found to be more suitable than other products for small-scale studies (Bai et al., 2018; Liu et al., 2019).

Characteristics of each dam were collected during fieldwork by Chan (2019) and provided by ASDF and SDW. Interviews and measurements were conducted within 30 sand dam communities, chosen due to the presence of a WDT from June 20 - July 12, 2019 (Appendix D). This part of the study gained ethical approval through the Cranfield University Research Ethics System (CURES) (CURES/8640/2019). Subsequently, 203 semi-structured interviews were conducted with the assistance of a translator in the homestead of sand dam users or at the handpump. Participants were selected for an interview using a snowball sampling method, on the basis that they used the handpump in question. Questions were centred around volume usage and ease of access to handpumps. The interviews were intended to identify the frequency of handpump usage and to determine which factors may cause people to use other water sources over handpumps. Water samples were taken at each handpump using a plastic cup, in which electrical conductivity was tested using a hand-held probe. This data derives from a relatively small interview sample, which could have provided biased results, and from self-reported metrics such as distance to fetch

water. Further, interviews were conducted at only one point in time at the start of the long dry season, yet it is recognised that some of the parameter values may vary temporally. Despite this, the presence of such information was far more valuable than no data.

Variables collected by Chan (2019) during fieldwork included perceived salinity (% of interviewees perceiving water as saline), abstraction limits (inc. only selling to members and limits to the number of jerry cans/person/day), livestock use (% of interviewees using the handpump for livestock), whether the dam is said to have ever run dry, presence of RWH tanks (% of interviewees with a tank), and actual salinity ($\mu\text{s/cm}$) (Appendix E). These variables were chosen based on knowledge regarding possible reasons for the use of such handpumps (Chan, 2019). Variables provided by ASDF and SDW included area of vertical face of dam wall (height * length of wall (m^2)), distance (average distance of round trip to handpump (km)), and user numbers. These were analysed using two models to provide insight into differences in abstraction between sites.

4.3.3 Data analysis

The rainfall data was analysed in Google Earth Engine. A single CHIRPS cell was selected for the coordinates of each dam to give a time series of daily rainfall data across the study period. The data from each site was averaged across the study period and from 1981 - 2021 to also give long term average rainfall.

Some abstraction data were missing due to signal and battery failures. Hourly abstraction of 0 m^3 (handpumps not used) was differentiated from missing data, which was represented by NA or an excluded data point. The raw hourly data was collated into daily, weekly, monthly, and seasonal data for the analysis.

To account for the missing data, all days with any missing hourly data were excluded so that total daily abstraction was based on a complete day. Following this, specific inclusion criteria were developed for different abstraction data sets depending on the analysis:

- To analyse patterns of abstraction, daily, monthly, and seasonal (m^3/day) data sets were used. Four outliers at one site of $>14 \text{ m}^3/\text{day}$ were removed from figures where necessary for clarity.
- To analyse the relationship between sand dam characteristics and abstraction volume, median monthly abstraction per person (m^3/day) was used. Only handpumps with data for all variables in the models were included.
- To analyse abstraction patterns in the long dry season, median weekly abstraction per person (L/day) was used. Only handpumps with >4 days-worth of data available for the last week of September (end of the long dry season) in at least one year were used.

These data sets were used to assess the contribution that each handpump was making to year-round water security. The data were coded and analysis performed in R Studio (RStudio Team, 2020) and Stata (StataCorp, 2021).

Descriptive and inferential statistics were used to explore general patterns of abstraction, both spatially and temporally. A Friedman Test (non parametric alternative to a one way ANOVA test, used when measurements of a group of subjects are taken over time), was used to assess statistical difference in median abstraction between seasons (m^3/day). Following a detrending of the data, total monthly abstraction was compared to total monthly rainfall at each site, using Spearman rank correlations (non-parametric version of a Pearson Test), to assess whether monthly abstraction varies significantly with rainfall.

To explore which characteristics may impact abstraction, two random effects regression models were used, as such models can handle panel data and are used to fit a relationship between two or more variables (Park, 2011). A Hausman test indicated the merits of a random over a fixed effects model. The dependent variable (median monthly abstraction per person (m^3/day)) was log transformed, enabling assumptions of a linear model to be met. Median, rather than mean abstraction was used due to the skewness of data. A monthly timescale was used to assess variation over the year. Significant (p) independent predictors of outcomes were assessed at $p < 0.05$, < 0.01 and < 0.001 . The first model included the independent variables: month, site, actual salinity, area of dam wall, livestock

usage, abstraction limits, and the proportion of interviewees with a RWH tank. The second model additionally included distance. Two models were used due to the limited number of sites with data available for distance. These variables were chosen for exploration purposes and due to previous research findings on what impacts abstraction (actual salinity, livestock use, RWH tank, and distance (Chan, 2019; Kelly et al., 2018; Rahman et al., 2017; van Schalkwyk, 1996)). Variables were dummy coded as categorical variables into two groups of roughly even sizes centred approximately around the average.

Finally, analysis in the last full week of September (used as a proxy for the end of the long dry season) assessed whether handpumps were providing at least sufficient drinking water by then. Due to the necessity of an improved source of water for drinking, the handpumps were classified based on a median weekly abstraction of 2 L/person/day and 4 L/person/day in the final full week of September, based on the minimum drinking water requirements cited by WHO (2016) in regular and hot climates respectively. Whilst it is recognised that at least 20 L/person/day is required for drinking, cooking, food hygiene, handwashing, and face washing, this analysis focuses on that purely required for drinking as a minimum starting point WHO (2016).

This was done to assess whether the handpumps could independently meet drinking water needs, in case no other water source was available. The handpumps were sorted into three groups based on a median weekly abstraction of 2 L/person/day (the lower cited minimum drinking water requirement (WHO, 2016)). Due to the 15% uncertainty in the data (Thomson et al., 2019), the groups were as follows: <1.7 L/person/day not providing sufficient water, 1.7 - 2.3 L/person/day potentially providing sufficient water, >2.3 L/person/day providing sufficient water. Any handpumps providing >4.6 L/person/day (derived from the minimum drinking requirement in hot climates (WHO, 2016)) with a 15% uncertainty, are marked with an X in Table 4-3. Values were based on per person abstraction using an average of 3.7 residents per household in Makueni (Knoema, 2019). However, differences in household size have been cited, with Augustine et al. (2014) citing an average of 6.2 residents per household in

Makueni. As a result of this, any handpumps with >2.3 L/person/day still being abstracted when using a household size of 6.2, are marked with a 0 in Table 4-3.

4.4 Results

4.4.1 Rainfall

Average monthly rainfall across the 26 study sites for the duration of the study period (April 2019 - October 2021) displayed the recognised Kenyan trend of two rainy and two dry seasons. Long term average yearly rainfall across the 26 study sites from 1981 - 2021 was 760 mm. Yearly rainfall for 2019, 2020, and 2021 was 1035 mm, 996 mm, and 726 mm respectively, highlighting 2019 and 2020 as wetter than average (CHIRPS, 2021).

On a seasonal level (based on literature derived seasons), the long rainy seasons in 2019 and 2021 were drier (160 mm and 264 mm respectively) than the long term average (286 mm), whilst 2020 was wetter (438 mm). This is in comparison to the short rainy season, which in 2019 was over two times greater (797 mm) than the average (375 mm), whilst 2020 and 2021 were slightly drier (332 mm and 369 mm respectively) (CHIRPS, 2021).

4.4.2 Patterns of daily abstraction

4.4.2.1 Spread of daily data

Across the months in which each handpump transmitter was live, the amount of missing daily data ranged from 6% at Woni 15 to 75% at Woni 16. Seven handpumps had $>50\%$ of data missing, whilst twelve had $<25\%$ of data missing. Not all transmitters were operational from April 2019 until October 2021, making it an unbalanced dataset. The dataset of daily abstraction showed a non-normal distribution, with a high positive skew to the right (skewness = 3.58), indicating a high proportion of small values. Of 11,610 daily data points, there were $n=840$ counts of 0 m³/day abstraction, whilst most values ($n=1,307$) lay between $>0 - 0.25$ m³/day.

4.4.2.2 Heterogeneity between sites

There was heterogeneity in daily abstraction patterns and volumes between handpumps. Four sites (Figure 4-2) have been used to represent the main patterns observed. Most handpumps saw peaks of abstraction in the long dry season ($n=17$) (Figure 4-2a), whilst some also saw peaks in the short dry season ($n=5$) (Figure 4-2b). Others saw additional peaks in the rainy seasons ($n=11$) (Figure 4-2c), whilst some showed similarly high levels of abstraction across the year with no distinct peaks ($n=3$) (Figure 4-2d). There was an observed decrease in abstraction through 20 analysed long dry seasons across 16 sites (Figure 4-2c), whilst 10 sites showed a distinct increase in abstraction across a total of 14 analysed long dry seasons. Due to this heterogeneity between handpumps, median daily abstraction, although 0.095 m^3 overall, varied greatly between individual sites from 0.002 m^3 at Ikanga to 2.96 m^3 at Woni 16 (Figure 4-3). Further, the maximum daily abstraction was 20.5 m^3 (at Wikwatyo), whilst the site with the smallest maximum abstraction was Ikanga at 1.7 m^3 .

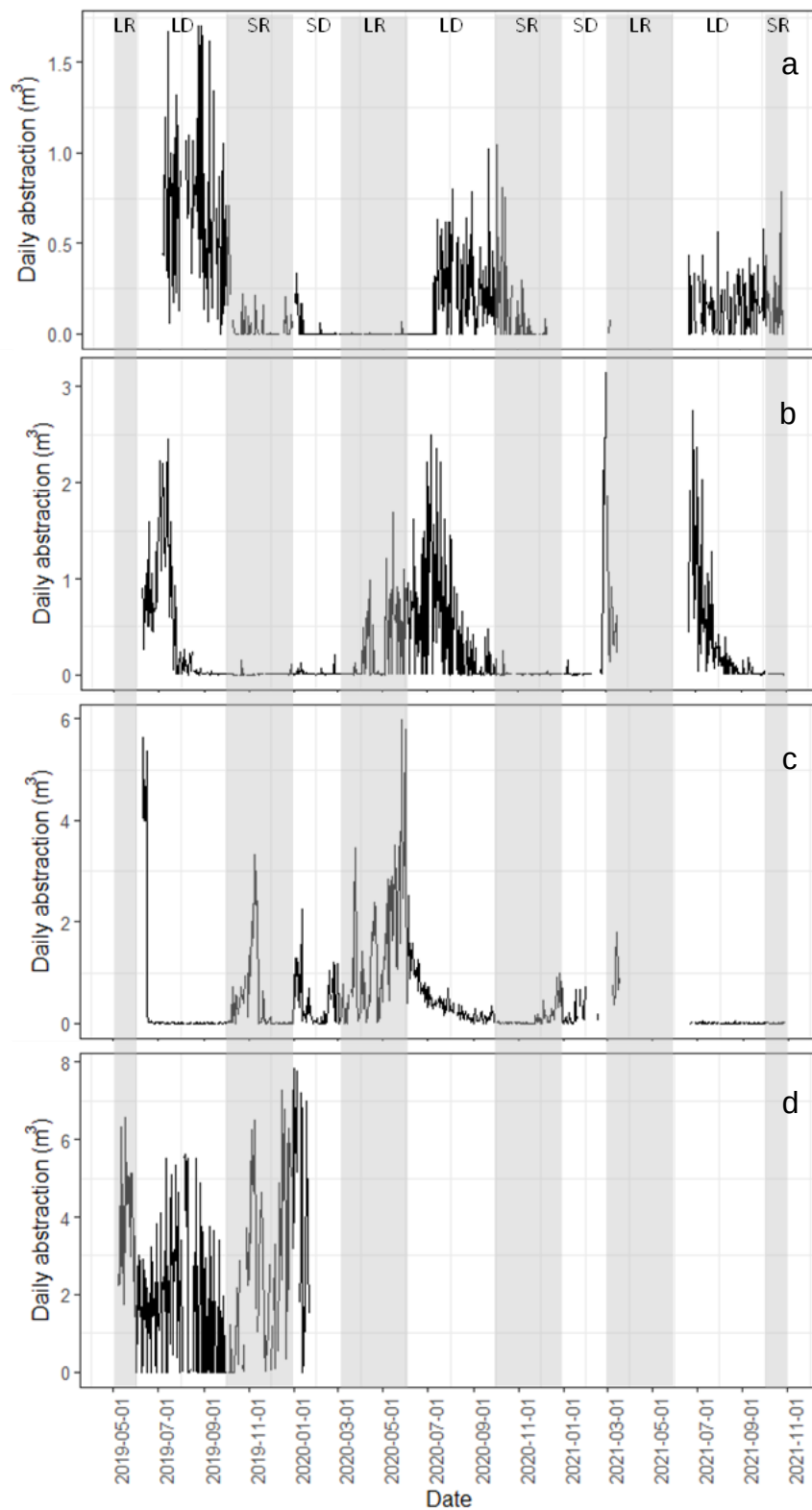


Figure 4-2: Daily time series of abstraction at sites (a) Ikanga, (b) Mapatano 18, (c) Makutano, and (d) Woni 15. Rainy season is shaded. LR = long rainy, LD = long dry, SR = short rainy, SD = short dry season

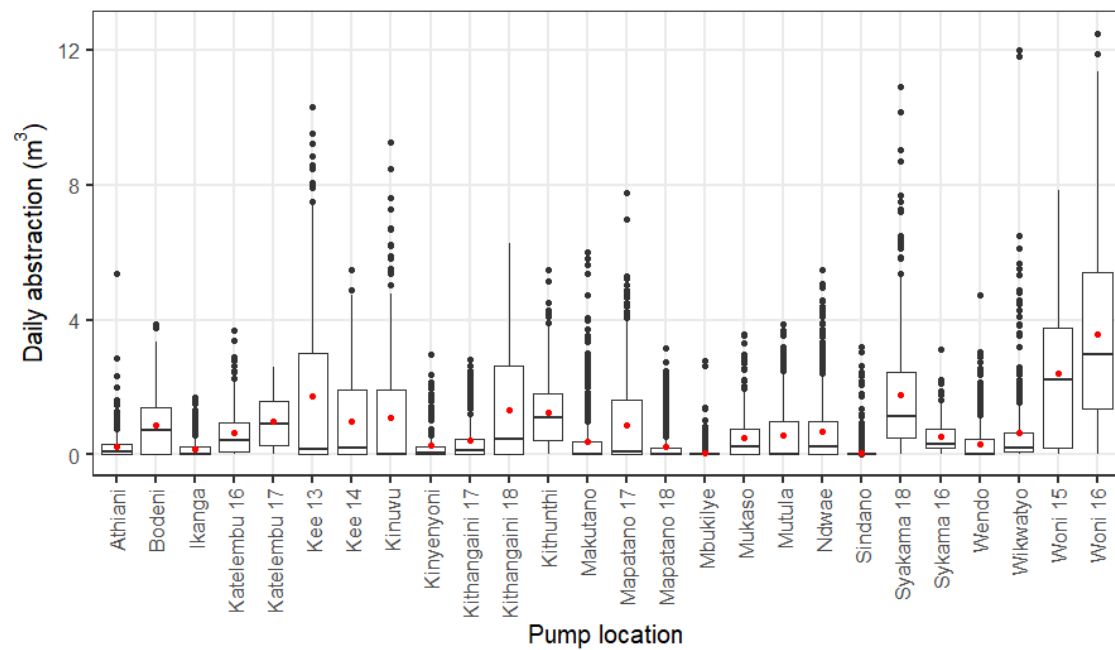


Figure 4-3: Daily abstraction (m^3) from each site across the study period. Red dot shows the mean value compared to the median line. Four outliers of $>14 \text{ m}^3/\text{day}$ have been removed for clarity.

4.4.2.3 Heterogeneity between seasons

Handpump use was heterogeneous between seasons (Figure 4-4). Median abstraction was highest in the long dry season ($0.4 \text{ m}^3/\text{day}$) compared to $0.01 \text{ m}^3/\text{day}$ in the short dry season. A Friedman Test indicated a significant ($p = 0.01$) difference in median daily abstraction between seasons (m^3/day) amongst individual sites.

Median monthly abstraction averaged across all sites showed a peak in the long dry season (August in 2019, July in 2020, and September in 2021). There is generally a decreasing trend in abstraction towards the end of the long dry season in 2019 and 2020. Lower levels of abstraction were observed throughout the rest of the year, with the lowest occurring at the end of the short rainy season in 2019, in the short dry season in 2020, and at the end of the long rainy season in 2021 (Figure 4-5).

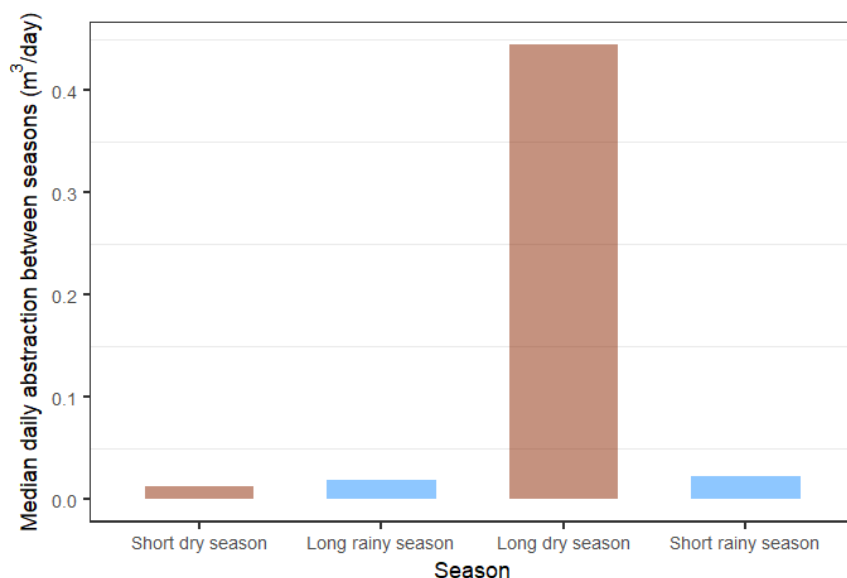


Figure 4-4: Median daily abstraction between seasons (m³/day) across all sites

Spearman rank correlations of total monthly abstraction compared to total monthly rainfall at each individual site indicated a significant negative correlation at four sites and a positive correlation at one: Athiani ($r=.45$, $p=0.04$), Kithunthi ($r=-.52$, $p=0.01$), Mapatano 17 ($r=-.48$, $p=0.01$) Mbukilye ($r=-.64$, $p=0.0003$), and

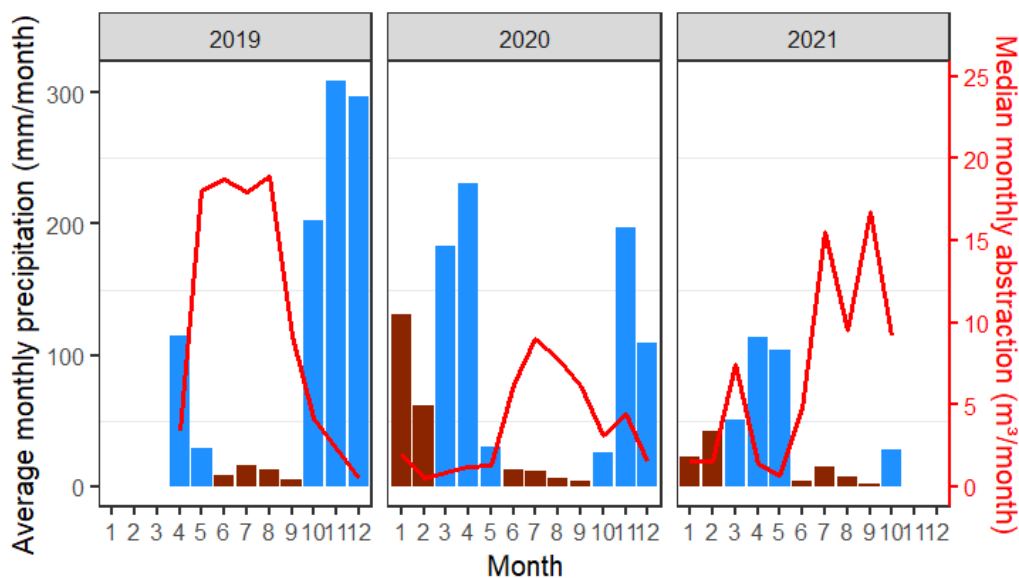


Figure 4-5: Median monthly abstraction (m³/month) (red line) and average monthly precipitation (mm/month) (brown bars = dry season and blue bars = rainy season) across all sites

Wendo ($r=-.74$, $p=2.15e-05$). The four latter sites indicated significantly higher monthly abstraction when rainfall was lower. Most of the other sites also show negative correlations. Nuances in the relationships indicate that: a.) it is an oversimplification to categorise the seasons based on accepted monthly distinctions, and b.) sand dams are predominantly but not only used during the driest periods, highlighting their multi-seasonal purpose.

4.4.3 Relationship between sand dam characteristics and abstraction volume

In order to assess whether any sand dam characteristics or individual behaviours were influencing abstraction, two random effects regression models were used. Table 4-1 highlights the descriptive statistics of the independent variables of sand dam characteristics or individual behaviour: actual salinity, area of vertical face of dam wall, livestock use, abstraction limits, presence of RWH tanks, distance, whether the dam is said to have ever run dry, and perceived salinity. The dependent variable (median monthly abstraction per person), and the control variables (month and handpump site) are also included.

Table 4-1: Variable characteristics used in regression models

Description	Value	Number of data points	Mean	Median	Min	Max
Dependant variable						
Median monthly abstraction per person (m³/day)	0 – 0.068	496	0.005	0.001	0	0.068
Categorical variables						
Actual salinity (µs/cm)	0 (<1000)	254	1218	938	208	3150
	1 (1000+)	215				
Area of vertical face of dam wall (m²) - height x length of wall	0 (<90)	356	105.9	72	36.6	420
	1 (90+)	117				
Livestock use (%) - % of interviewees using the handpumps for livestock	0 (<40)	228	40.7	33	0	100
	1 (40+)	212				
Abstraction limits (inc. only selling to members, limited number of jerry cans/person/day)	0 (no)	151	0.7	1	0	1
	1 (yes)	289				
RWH tank (%) - of interviewees with tanks	0 (<42)	245	43.6	40	0	83
	1 (42+)	172				
Distance (km) - average distance of round trip to handpump	0 (0.5)	185	0.7	0.5	0.5	2.1
	1 (>0.5)	166				
Ever run dry	0 (no)	275	0.1	0	0	1
	1 (yes)	44				
Perceived salinity (%) - % of interviewees perceiving water as saline	0 (<60)	161	50	50	0	100
	1 (60+)	253				
Control variables						
Month		31			04. 2019	10. 2021
Handpump site		26				

Data on five of the independent variables of sand dam characteristics or behaviours (Table 4-1): actual salinity, area of wall, livestock, abstraction limits, and RWH tank, whilst controlling for month and pump, were compared to log median monthly abstraction per person (m³/day) in random effects regression model 1 (Table 4-2). Perceived salinity was excluded due to high collinearity with actual salinity. Ever run dry and distance were removed due to the loss of data due to 8 and 9 handpumps respectively having no values for these variables. This first model explained 47% of the variation in abstraction. 75% of the long dry months during the three years were found to have significantly higher abstraction than the reference month of January 2020. Abstraction was also significantly higher in the rainy seasons of May 2019, Oct 2020, and October 2021. Sites where actual salinity was higher, dam wall area was larger, and more people were using the water for livestock had significantly higher levels of abstraction. Abstraction limits and the proportion of people with RWH tanks were not significant.

Distance was included in the second regression model, using a reduced number of handpumps (Table 4-2). The second model explained 50% of the variation in abstraction. Sites where actual salinity was higher, dam wall area was larger, and abstraction limits were in place had significantly higher levels of abstraction. Livestock use, the proportion of people with RWH tanks, and distance were not significant. As distance was not significant in model 2 and given the reduced number of sites used, the first model is the focus of the discussion in Chapter 4.5.

Table 4-2: Results of the regression analyses

	Model 1	Model 2
Control variables		
Actual salinity	2.49***	1.86**
Area of wall	4.13***	3.17***
Livestock use	1.25**	0.80
Abstraction limits	0.71	1.75*
RWH tank	0.79	-0.37

Distance	-	-0.96
Observations	390	284
Groups	22	16
R ²	0.47	0.50
Wald chi ²	301.44	237.88
Max VIF	1.88	2.76

p < 0.05, **p < 0.01, *p < 0.001*

Regression analysis of the relationship between independent variables highlighted that, in general, sites with lower actual salinity are used primarily for domestic purposes, whilst those with higher levels of salinity are used for a wider variety of purposes including irrigation and livestock. One anomaly (Wendo), however, had the highest recorded salinity levels and was only being used for domestic purposes. 100% of users of this sand dam were using other sources, so potentially they use these for domestic supply when the sand dam is exceptionally saline, and only use the sand dam when other sources are dry. There was no notable relationship between actual salinity and both maturity of the dam and the percentage of people using other sources. This suggests that age of the sand dams is not necessarily a predictor of how saline the water will be, with the local geology likely being a greater controlling factor. Similarly, whether actual salinity is high or low, a large proportion of sand dam users normally report to using other additional sources. As the interviewer did not ask at what time of the year the other sources were being used, it is difficult to conclude whether other sources are used concurrently with sand dams or whether they are prioritised over sand dams in the rainy season when they are available. However, as RWH tank use was not significantly correlated with sand dam abstraction, this suggests that people are using other sources at different times of the year to sand dam use, at least to a degree.

4.4.4 Long dry season analysis

Of the 26 handpumps, 22 had abstraction data available for the last full week of at least one long dry season. Of these sites, 21 had some water still being

abstracted, indicating that they were providing water when access to other sources may have been compromised. Median daily abstraction in this week averaged across the three years across the 22 sites was 0.24 m³/day. This varied, however, between 0 m³/day at Bodeni and 5.92 m³/day at Kee 13.

From these 22 handpumps, using a household size of 3.7, 32% (N=7) of sites were classed as providing sufficient water (>2.3 L/person/day) by the end of each long dry season (2019 - 2022): being able to meet user's minimum drinking needs. A further 27% (N=6) met this need by the end of at least one long dry season. Of these 13 handpumps, 85% (N=11) were providing >4.6 L/person/day: the drinking water needed in hot climates (WHO, 2016) in at least one long dry season (indicated by an X in Table 4-3). These handpumps were able to meet user's drinking water needs independently of other sources (blue in Table 4-3).

Of the remaining handpumps, 36% (N=8) were not providing sufficient water (<1.7 L): failing to meet the drinking water needs of their users in any year (orange in Table 4-3). One handpump (Makutano) was classed as 'potentially providing sufficient water' in 2020 (between 1.7 - 2.3 L) (white in Table 4-3).

Finally, of the 21 seasons (blue in Table 4-3) in which >2.3 L was being abstracted using a household size of 3.7, 81% (N=17) still had >2.3 L being abstracted when using a household size of 6.2 (indicated by a 0 in Table 4-3). This indicates that the majority of sites would still have provided sufficient water to meet drinking water needs even with a larger user population.

Table 4-3: Handpumps and years where minimum user drinking needs were and were not being met by the last full week of the long dry season (September) based on median weekly abstraction (L/person/day) using an average household size of 3.7. Blue = >2.3 L/person/day (providing sufficient water). Orange = <1.7 L/person/day (not providing sufficient water). White = 1.7 - 2.3 L/person/day (potentially providing sufficient water). Grey dash = missing data. X = providing >4.6 L/person/day. 0 = providing >2.3 L/person/day when using a household size of 6.2

	Site	No. of households	2019	2020	2021
1	Athiani	18			
2	Bodeni	9			
3	Ikanga	12	X 0		
4	Katelembu 16	30	X 0		
5	Katelembu 17	30			
6	Kee 13	100	X 0		
7	Kee 14	60			
8	Kinuvu	46			
9	Kinyenyoni	47			
10	Kithangaini 17	73			
11	Kithangaini 18	97			
12	Kithunthi	98	X 0	X 0	0
13	Makutano	20			
14	Mapatano 17	12	X 0	X 0	X 0
15	Mapatano 18	19			
16	Mbukilye	27			
17	Mukaso	86			
18	Mutula	26	X 0		X 0
19	Ndwae	43		X 0	X 0
20	Sindano	31			
21	Syakama 16	51			
22	Syakama 18	62			X 0
23	Wendo	29		X 0	
24	Wikwatyo	21	X 0		
25	Woni 15	55			
26	Woni 16	72			X 0

4.5 Discussion

The contribution that sand dam handpumps make to water security is fundamental to their practicality and usefulness as a water source in drylands. It was hypothesised that sand dams improve a community's year-round water security by providing water from handpumps in the dry season. As the first to analyse a long-term time series of abstraction data from sand dams, this study supports this hypothesis in general, with the majority of sites having evidence of abstraction by the end of the long dry season. However, heterogeneity between sites and missing data make general conclusions difficult.

4.5.1 Temporal abstraction trends

Abstraction from the handpumps is highly heterogeneous between seasons. When rainfall is higher, utilisation of handpumps is generally lower. This is consistent with the findings of Thomson et al. (2019) who studied the relationship between rainfall and groundwater use in Kwale County on Kenya's southern coast. They found the highest weekly abstraction (average 2.3 m³/pump/day) to be in the last week of the short dry season. This was three times greater than that of the second week of May (average of 0.8 m³/pump/day), around the peak of the rains.

Lower levels of abstraction observed in months outside of the dry season are hypothesised to be linked to the recorded increase in use of multiple sources in the rainy season (Arouna & Dabbert, 2010; Elliott et al., 2017; Kelly et al., 2018). Despite the assumed availability of water in the sand dams in the rainy season, people may choose to use other sources for numerous reasons including cost, labour, and convenience, the latter of which is often cited as the most influential (Dessalegn et al., 2013). Many sources, however, are compromised in the dry season, forcing use of alternative sources (Chan, 2019; Kaptué et al., 2013; Kelly et al., 2018; van Houweling, 2016), likely explaining why sand dam handpump abstraction increases. Furthermore, low abstraction from sand dams in the short dry season may also be due to greater water availability in more convenient sources such as household RHW tanks in this season. This could be due to the shorter duration of this dry season and the greater recharge from rainfall in the previous (short) rainy season (Gichuki, 2000).

This study found a maximum of a 34-times increase in median daily abstraction (m^3/day) in the long dry season compared to other seasons. Neufeld et al. (2020) found abstraction from sand dams in the Ukambani region of Kenya to increase from around 50 - 70% of households from the rainy to dry season, whilst RWH tank usage fell from >80 - 10%. Thomson et al. (2019) similarly found that 86% of households used handpumps (not at sand dam sites) as their main drinking water source in the dry season compared to 6% in the rainy season. Participants interviewed by Chan (2019) reported to fetching less or no water from handpumps when their RWH tanks are full. This supports the importance of convenience when choosing a preferred water source. Whilst distance wasn't a significant predictor of abstraction in this study, this is likely because the use of sand dams was found to be fairly independent of RWH tank use and people lived on average only 0.7 km from the dams. Understanding the response of water management techniques, such as sand dams to rainfall, highlights their resilience to future changes in climate and their applicability in drought prone areas (Macdonald et al., 2019). By providing insight into when abstraction is lower, this study can help to inform water providers on times of the year when water supply from other sources such as vendors may need expanding at certain sites.

4.5.2 Heterogeneity in abstraction

The results show high heterogeneity in abstraction between handpumps, with median daily abstraction ranging from 0.002 m^3 - 2.96 m^3 . Whilst abstraction rates from handpumps may be low at certain sites, it is important to remember that this is not the only abstraction method from sand dams. Whilst no studies have specifically evaluated water volume abstracted from agricultural wells and scoop holes compared to handpumps, Quinn et al., (2019) observed scoop hole abstraction at two sites and estimated abstraction rates of between 0.4 and $0.6 \text{ m}^3/\text{day}$. This is substantially greater than the median handpump abstraction volume calculated in this study, indicating the greater average contribution to water security that the studied sites may be providing beyond that shown by the telemetered data.

Modelling of sand dam characteristics against abstraction volume goes some way to explaining the variation seen across sites. In the regression model, abstraction was significantly higher at sites with higher actual salinity, larger dam walls and where a greater proportion of interviewees use the water for livestock. Evidently, as a maximum of 50% of variation in abstraction was explained by the models, there are other reasons apart from those included in this study which impact abstraction.

Possible other reasons for this heterogeneity include water availability due to sand dam characteristics, including alluvium grain size and sorting, depth of sediment, width of riverbed, and slope of banks (Aerts et al., 2007; Borst & Haas, 2006; Jansen, 2007; Nissen-Petersen, 2006; Quinn et al., 2019; Strohschein, 2016; Trinchera et al., 2015). The decrease in abstraction across the long dry season at some sites supports that the reduction here may be due to a reduction in available water. At other sites, where there is a notable increase or relatively stable trend in abstraction across the long dry season, other factors may contribute to the heterogeneity in abstraction volumes. These include environmental characteristics, such as rainfall, soil, geology, accessibility, topography, and stream order (Jeil et al., 2020; Ngugi et al., 2020; Thwala, 2010; Wrisdale et al., 2017; van Houweling, 2016), as well as social factors, including number of users, average distance to each dam, quality, safety, availability and use of other sources, perceptions, tradition, price, and water use practices, may impact use (Chan, 2019; Devoto et al., 2012; Elliott et al., 2017; Howard, 2002; Jiang & Rohendi, 2018; Parameswari et al., 2016; WHO & UNICEF, 2017).

4.5.2.1 Actual salinity

Abstraction was significantly higher at sites with salinity levels $>1000 \mu\text{S/cm}$. The WHO (2017) permissible level of electrical conductivity for drinking water is $2500 \mu\text{S/cm}$, of which 12% ($N=3$) of samples exceeded. This is likely due to the entrapment of salts within the alluvium and an absence of regular flushing out of such salts, leading to an accumulation (Kitheka, 2017, 2019). It is important to note, however, that salinity is known to vary seasonally, with levels found to be higher in the dry season (Kitheka, 2016). As testing was done at only one point

in time (June-July), the measured values likely do not represent this seasonal variation. People often seek to use alternative sources to saline water for drinking (Kinniburgh & Smedley, 2001). This is due to perceived health implications, such as hypertension, (pre)eclampsia and infant mortality (in pregnant women), respiratory infection, and kidney disease (al Nahian et al., 2018; Radwanur & Talukder, 2015; Shammi et al., 2019). As only a small part of daily water use is used for drinking, however, abstraction was found to be higher at locations used to meet other needs, with individuals continuing to use saline water for purposes other than drinking. For example, despite measured salinity being higher at Woni 16, this handpump was used more than Woni 15, with people continuing to use Woni 16 for livestock and domestic use, compared to Woni 15, which was used for cooking and drinking.

4.5.2.2 Dam wall area

At 25% of sites the dam wall area is $\geq 90 \text{ m}^2$ (Table 4-1), at which abstraction was significantly higher. This is likely due to a greater volume of sand being able to build up behind a larger dam wall, and therefore a greater volume of water being stored (Borst & Haas, 2006; Jansen, 2007; Loon & Droogers, 2006; Maddrell & Neal, 2012).

4.5.2.3 Livestock

At 48% of sites >40% of interviewees were using the handpump water for livestock (Table 4-1). These sites experienced significantly higher abstraction. When comparing interviewees' self-reported abstraction volumes to livestock usage, it was found that those using the pumps for livestock abstracted 31% more water. It is estimated that a bare minimum of 20 L/person/day is required to meet basic domestic water needs (WHO, 2003) compared to higher requirements for livestock, with growing heifers of 182 kg in 32.2 °C having an approximate daily water intake of 40 L (Subcommittee on Beef Cattle Nutrition et al., 2000). This therefore explains the higher water requirements where handpumps are being used for livestock.

4.5.2.4 Variables that did not predict abstraction volume

Abstraction limits did not significantly predict abstraction in the model, suggesting their lack of impact on water use. Sand dam users on the ground can likely assess the availability of water from a sand dam to a better extent than a model can do. They will continue to do what they consider necessary to conserve and sustain water resources.

Finally, the lack of significant impact of RWH tanks on abstraction suggests people's reliance on handpumps independently of RWH tanks. This is likely because RWH tanks are used to a greater extent in the rainy season (Adekalu et al., 2002; Boelee et al., 2013; Elliott et al., 2017; Özdemir et al., 2011; Shaheed et al., 2014), compared to sand dam handpumps which are used more in the dry season. This indicates that a holistic view of water management needs to be taken, considering all available options as one managed whole.

4.5.3 Drinking water needs

Of the 22 handpumps with available data, 21 had some water abstracted by the last week of the long dry season (median daily abstraction of 0.24 m³), indicating a contribution to year-round water security. This is consistent with Borst et al. (2006), Hanson & Nilsson (1986), Jansen (2007), Quilis et al. (2009), and Simon (2019) who cite and measure the success of sand dams in retaining water until the end of the dry season. Whilst this is true of some sites, the level to which sand dams can meet water needs independently of other sources is questionable at some sites due to high heterogeneity in handpump abstraction. The variation in abstraction between years shows that whilst some handpumps can provide 2 L/person/day by the end of some long dry seasons, factors impacting abstraction may change over time. These include the availability of other sources, population numbers which may not remain stable, variable rainfall rates, and the maturity of the dam.

The results from Table 4-3 clearly demonstrate that the level of abstraction is not sufficient to support the drinking needs of all users of all handpumps in all years. This heterogeneity is consistent with the findings of Ngugi et al. (2020). They

used a water requirement calculation using the number of households ($n=50$), persons per household ($n=5.98$), daily per capita water requirements (20 L), daily average household demand for livestock (119 L) and number of days in the long dry season (150). A survey was used to assess whether a resulting water requirement of 1800 m³ throughout the dry season was being met. They found that about 42% of dams (using handpump, scoop holes, and pools) could meet household water demand throughout the whole long dry season. This compares to the current study, which found that 59% of sites (using only handpumps) were meeting only minimum drinking water needs by the end of at least one long dry season. The study by Ngugi et al. (2020) was based on reported user numbers, estimated water requirements, and previous study's water volume estimates. The report of 42% of dams meeting household demand, however, is not consistent with their other result which claimed that only 36% of dams would have water in by the end of the long dry season. Whilst using different source types and minimum water demand estimates, the results are an important reminder and corroboration with results from the current study that whilst some sand dams may be able to meet water demands, others cannot.

Whilst sites were selected due to a known reasonable signal across the period that each transmitter was live there is some missing data. Uneven proportions of missing data in different seasons and sites place limitations on the comparisons that can be made between sites and time periods. This is an inherent challenge in certain, especially rural settings across the world. This study in part overcame this uncertainty by using average values and developing exclusion criteria. It is also argued that the benefits of using WDT over or in coordination with traditional methods of data collection outweigh the uncertainties. Using this data, the study has positively contributed to the literature on sand dam's contribution to water security. Whilst there is heterogeneity in abstraction between seasons and sites, many handpumps are still being used by the end of the long dry season, with significantly more abstraction seen at sites with higher salinity, larger dam walls, and higher livestock usage. Sand dams can therefore be seen as an effective dryland water source, especially useful in the dry season.

4.6 Conclusion

As the first study to analyse multi-year abstraction trends from sand dam handpumps, it reveals, quantitatively, the positive contribution that sand dams can make to year-round water security, by providing a water source by the end of the long dry season when other water sources are compromised. Of 22 handpumps with abstraction data for the end of at least one long dry season, 59% suggest they can meet drinking water needs of all users independently of other sources.

Having said this, heterogeneity in abstraction is a reminder that not all sand dams behave the same. Certain sand dams are always likely to have higher levels of abstraction than others, such as those with higher levels of salinity, larger dam walls, and higher livestock use. The findings of low abstraction from certain handpumps and in certain months challenge sweeping statements in some literature professing the success and perfection of all sand dams, which are neither accurate nor helpful. Abstraction levels are not synonymous with water storage in the dam, however, and there are many confounding factors impacting abstraction. Therefore, without further research directly comparing field-based data on water storage, telemetered handpump abstraction data, and abstraction from other sources, their true capabilities are unknown. Having said this, high abstraction, and sustained water availability by the end of the long dry season at many sites profess the positive contribution that sand dams can make to a community's water supply, offering opportunities for further success in the future.

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5 Insights from Electrical Resistivity Tomography on the hydrogeological interaction between sand dams and the weathered basement aquifer

5.1 Abstract

Sand dams, composed of recent alluvial aquifers behind concrete dam walls, are a water management technique in drylands. However, their level of hydraulic connectivity with their surrounding weathered basement aquifer is unknown. Their behaviour as groundwater storage or aquifer recharge structures is therefore debated. This study aims to constrain the hydrogeological uncertainty of sand dam's connectivity with their surrounding aquifer in order to better understand their ability to meet water needs and improve dryland water security. The study is the first to use 2D geophysics (Electrical Resistivity Tomography) to provide evidence of variable lateral and longitudinal seepage from sand dam alluvial aquifers into the weathered basement at three mature and three newly built sand dams. A generally greater hydraulic connectivity was found between sand dams and their surrounding aquifer than was previously thought, with sites providing a local recharge function rather than existing as isolated storage structures. This improved understanding is beneficial for both site selection and the performance of sand dams. The study highlights sites where water storage will be predominantly constrained to the alluvium and surrounding shallow weathered basement aquifers and sites underlain by thicker weathered basement deposits, which lose more water to the surrounding aquifer. Such knowledge can help ensure that maximum benefits are derived from the construction of a sand dam depending on its intended purpose.

5.2 Introduction

Drylands are defined by the Aridity Index as areas where the ratio of precipitation to potential evapotranspiration (P/PET) is <0.65 (Middleton et al., 1992). By the end of the 21st century they are predicted to become home to up to 5.2 billion people (Koutroulis, 2019), however, they possess only 8% of global renewable water resources (Právělie, 2016). For current and future populations living in

drylands, effective water management is, therefore, crucial for promoting sustainable livelihoods.

More than 70% of the world's drylands are located in developing countries (Safriel et al., 2005). With limited access to safely managed water, alternative improved water sources are essential to strengthen resilience and ensure universal access to safely managed water. Water harvesting methods that collect and store surface water and/or increase the availability of groundwater are one such source. Sand dams, forming enhanced alluvial aquifers, which are recharged by streamflow, are one example (Maddrell, 2018).

Ephemeral rivers are common in drylands, with infiltration through such riverbeds considered an important pathway for recharging alluvial and basement aquifers (Philipp & Grundmann, 2013). Such recharge can be artificially increased by storing surface water in order to promote groundwater recharge to local aquifers (McCallum et al., 2013; Modie et al., 2022; Philipp and Grundmann, 2013). Studies on groundwater recharge in drylands have been conducted across the world, through the use of techniques including stable isotope data, water table fluctuation models, monitoring wells, and chloride mass balance (Modie et al., 2022; Scanlon et al., 2006; Sorensen et al., 2024). Having said this, according to Sorensen et al. (2024), there are limited highly instrumented observatories to investigate recharge processes, which limits the understanding of such recharge.

Sand dams are used on ephemeral rivers in drylands around the world. Sand dams store surface water and increase water availability for abstraction. However, there is uncertainty around their hydraulic connectivity with their surrounding aquifer (Hut et al., 2008; Yifru et al., 2021). Their relative importance for groundwater storage in the alluvium or recharge to the surrounding weathered basement aquifer is, therefore, contested.

Studies have modelled (Borst & Haas, 2006; Ndekezi et al., 2023; Quinn et al., 2019; Yifru et al., 2020), remotely sensed (Eisma & Merwade, 2021; Manzi & Kuria, 2011; Neufeld et al., 2021; Ryan & Elsner, 2016), or assumed (Eisma & Merwade, 2020; Hoogmoed et al., 2007; Hut et al., 2008; Loon & Droogers, 2006; Maddrell, 2018; Quilis et al., 2009) seepage of water from sand dams laterally

into the weathered basement and longitudinally under or around the dam wall. Hut et al. (2008) found the impact of sand dams on groundwater levels in riverbanks directly upstream of the dam walls to range from 70 – 80 m into the riverbanks. The sub-vertical component of lateral seepage into the underlying weathered basement via the river channel base, which is especially difficult to monitor, is usually either assumed (Eisma & Merwade, 2020; Maddrell, 2018; Quinn et al., 2019) or discounted (Ertsen et al., 2005; Nissen-Petersen, 1997). Seepage would reduce storage in the trapped alluvium but would allow potentially greater recharge to the surrounding aquifer.

Whilst sand dams can be constructed to serve different purposes of storage or recharge, their hydraulic connectivity with their surrounding environment is rarely explored pre-construction. This general lack of consensus on the nature of hydraulic connectivity between sand dams and their surrounding aquifer is, therefore, the basis for this research. The study aims to determine whether sand dams are losing water laterally (and sub-vertically), and longitudinally into the surrounding aquifer and downstream respectively. This will help to indicate whether they exist as storage or MAR structures. Studies in similar drylands environments have utilised geophysical techniques to investigate hydrogeological connections between alluvium and underlying crystalline basement (Issoufou Ousmane et al., 2023). This study therefore sought to contribute to this existing knowledge in the specific context of sand dams, being the first to use 2D geophysics at sand dam sites and to collect field-based data before and after sand dam construction. It provides evidence into the reality of the hydrogeological system surrounding sand dams and how the presence of loss pathways varies between sites.

5.3 Methods

5.3.1 Study area

The study took place at six sites in the north and south of Makueni County, Kenya (Figure 5-1). According to the Aridity index, the area belongs to the semi-arid and dry sub-humid regions ($0.2 < P/PET < 0.65$) (UNEP-WCMC, 2007). Annual precipitation from 1981 - 2022 at the six sites varied between 586 and 797 mm

at the southern and northern sites respectively (CHIRPS, 2021) (Figure 5-1). The northern sites are at a higher elevation of >1,100 m asl, whilst the southern sites are at <850 m asl and are in slightly less incised valleys. The catchment size for each site is similarly small, with the largest measuring approximately 72 km².

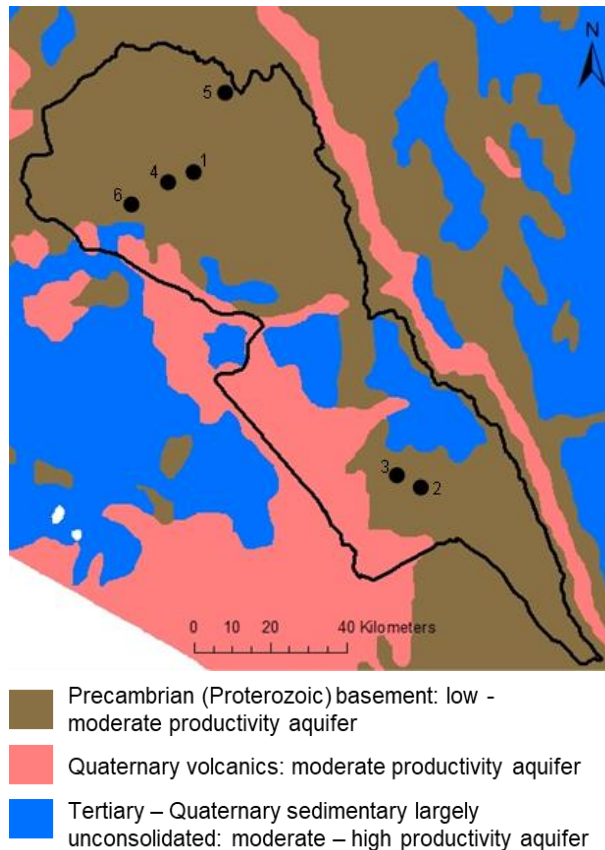


Figure 5-1: Geological and hydrogeological map of Makueni County, Southeast Kenya indicating aquifer productivity and study sites: (1) Kithunthi; (2) Kipico; (3) Ngulai; (4) Nthonzweni; (5) Wambiti; (6) Kyakivandi. Reproduced with the permission of the British Geological Survey © UKRI [2024]. All Rights Reserved

Three mature sand dam sites: Kithunthi, Kipico, and Ngulai (constructed in 2016, 2016, and 2013 respectively), and three new sites: Nthonzweni, Wambiti, and Kyakivandi (constructed in 2022) were studied. Kipico and Ngulai were selected because of available data from Quinn et al. (2019) who conducted a water balance to assess flow rates at three sand dams. Their third site was not selected due to rocky ground conditions that were unsuitable for the use of geophysical equipment. A third mature site (Kithunthi) was selected based on suitable ground conditions, telemetered data indicating prolonged water storage, available abstraction data, and reasonable accessibility from the other sites. The three new sites were selected due to planned construction during the 2022

fieldwork period, with suitable ground conditions, and reasonable accessibility from the mature sites.

5.3.1.1 Geological and hydrogeological setting

The sites, in common with much of the Basement Complex geology across approximately 34% of Africa are predominantly composed of granitoid and biotite gneiss, with some minor schist (Baker, 1952; Dodson, 1953; MacDonald & Calow, 2009). Subject to weathering, Precambrian basement rocks can establish a weathered profile typically comprising residual soil and saprolite, together forming the regolith, and saprock and fresh, unweathered bedrock, together forming the crystalline bedrock (Bianchi et al., 2020; Rusagara et al., 2022; Wright & Burgess, 1992; Zarate et al., 2021). (Figure 5-2). Aquifers form either in the primary porosity of river alluvium or in the secondary porosity of the underlying weathered bedrock (Bakundukize et al., 2016; Elster et al., 2014; Wright & Burgess, 1992). Typically, the saprolite has a predominantly storage function and the saprock a transmissive one (Bakundukize et al., 2016; Elster et al., 2014) (Figure 5-2).

The base of the alluvium is at the interface between surface and groundwater flow (Brunner et al., 2017). The alluvial sand dam aquifer and groundwater in the weathered basement below can be either hydraulically connected or

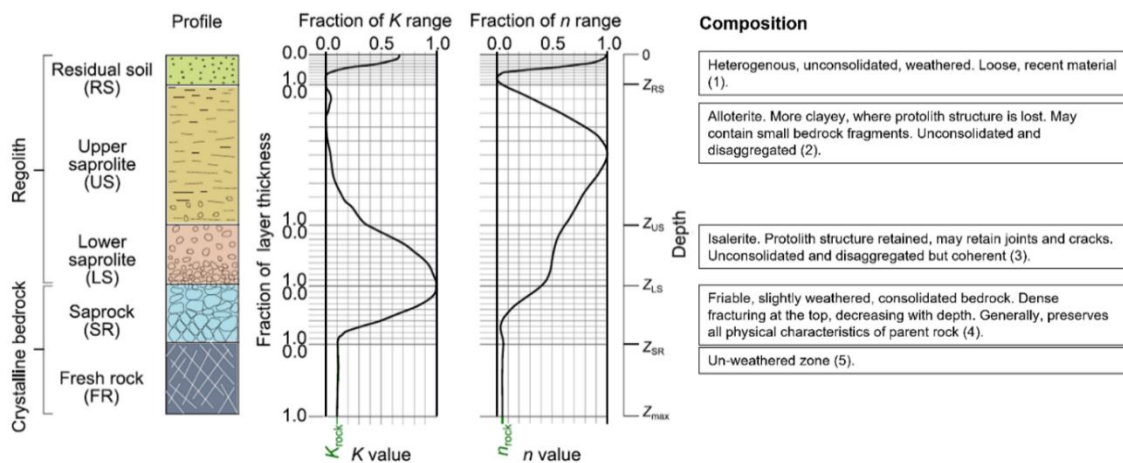


Figure 5-2: Conceptual model of physical heterogeneity in a weathered basement aquifer, highlighting K (hydraulic conductivity) and n (porosity) (Adapted from Bianchi et al. 2020 under the CC BY 4.0 licence. Contains British Geological Survey material © UKRI 2020) and typical compositions. (1) (Bakundukize et al., 2016; Kayode et al., 2022). (2) (Ulusoy & Kadioğlu, 2021). (3) (Wright & Burgess, 1992). (4) (Wright & Burgess, 1992). (5) (Bianchi et al., 2020)

disconnected, largely depending on the nature of the saprolite and climatic conditions (Watson et al., 2021; Wright & Burgess, 1992). During sufficient rainfall, surface and groundwater systems in drylands can be connected (Watson et al., 2021). During dryer periods, the two may not be connected. If the saprolite is very clay-rich and therefore relatively impermeable, any water stored in the alluvial riverbed may form a pseudo-perched aquifer, with an aquiclude limiting flow to the underlying groundwater. Otherwise, a disconnected stream may form, with any water stored in the alluvium recharging the water table but separated by an unsaturated zone.

In the dry season, the depth to the water table often prevents discharge along the river channel. Through the water stored in the alluvium after the construction of a sand dam, the water table is locally raised in the riverbed (Figure 5-3). This creates a groundwater mound (Borst & Haas, 2006; Strohschein, 2016), where the water table is higher than in the adjacent riverbanks, allowing water to seep from the alluvium into the surrounding aquifer. This water can recharge the water table in the weathered basement until equilibrium is reached if there is a connection between the two. Some water in the riparian zone is hypothesised to be lost to evapotranspiration by surface vegetation (Strohschein, 2016; Yao et al., 2018). Consequentially, much of the seepage from sand dams may not be beneficial to people.

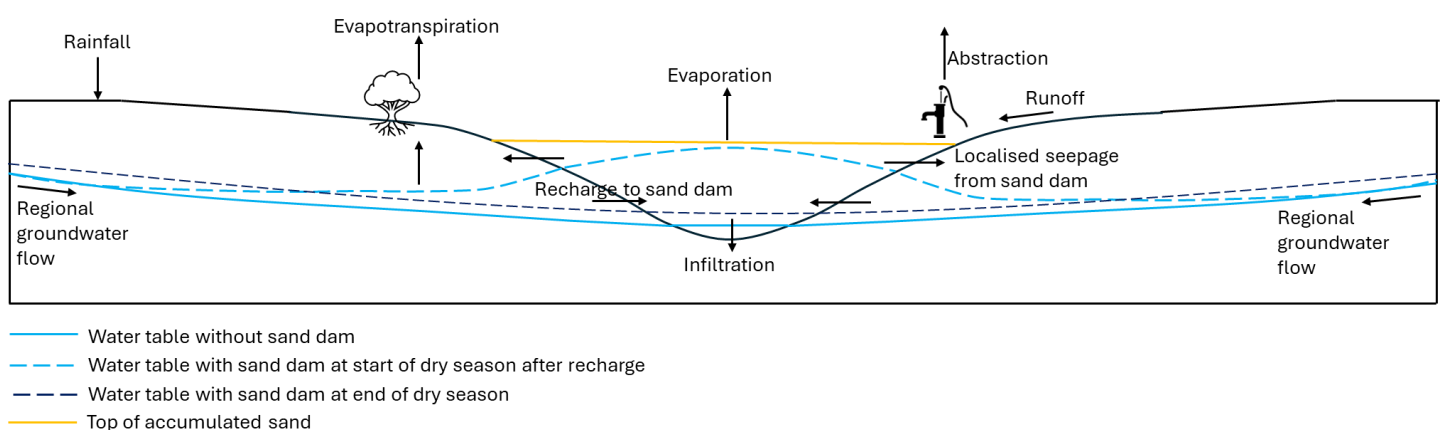


Figure 5-3: Conceptualisation of the impact of a sand dam on water levels in the riverbed and surrounding riverbanks based on previous studies (Borst & Haas, 2006; Strohschein, 2016)

5.3.2 Data collection

5.3.2.1 Field studies

Two field studies in Kenya were conducted in February - March 2022 and 2023. The fieldwork involved geophysical surveys using ERT and Induced Polarisation (IP), and field observations.

Electrical resistivity (called resistivity from here) methods are used to identify geological structures by proxy due to differences between resistivity values of subsurface materials (Lowrie, 2007). ERT is a 2D multi-electrode geophysical method that relies on an injection of current and the response of voltage to measure a material's resistivity. IP can be collected during the same measurement cycle and measures a material's chargeability. In theory, it can help to differentiate between clay and water, which both have low resistivity values, whilst the former has much higher IP values (Shao et al., 2021). For a detailed description of the ERT and IP techniques, refer to Loke (1999) and Lowrie (2007) respectively. ERT was chosen over other geophysical methods due to its common use and merit in groundwater studies, its sensitivity to both lithology and water content, and its 2D capabilities (Ebong et al., 2021; Kumar et al., 2016; Saad et al., 2012).

An ABEM Terrameter LS resistivity meter was used to collect the ERT data. Two array types: Gradient and Schlumberger, were used to investigate repeatability of results. The gradient array makes use of the multi-channel function of the equipment, meaning it can collect multiple potential measurements for each current pair and, according to Dahlin & Zhou (2006), gives better imaging resolution than conventionally used arrays (Wenner and Schlumberger). Schlumberger also chosen as it is better for IP measurements and has good horizontal and satisfactory vertical resolution (Lowrie, 2007). Two cables and 41 electrodes were used in each profile. Salt water was added around the electrodes to improve ground contact due to soil aridity.

Between four and five main profiles were undertaken at each site (Figure 5-4) to assess: a.) the extent of water saturation adjacent to the riverbed to explore lateral seepage, b.) the composition of the underlying weathered basement and

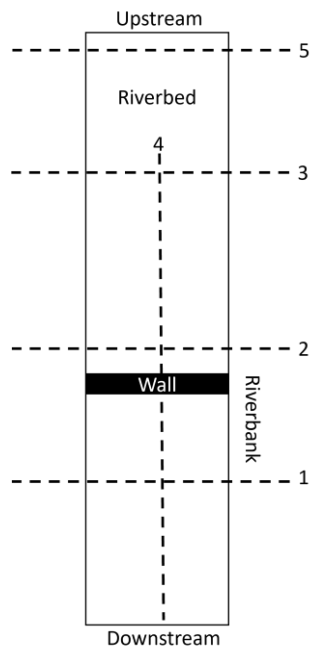


Figure 5-4: ERT profile locations. Profiles 1-3 (parallel) and 4 (perpendicular) were conducted at all sites. Profile 5 was conducted only at Kipico

change in water saturation pre- and post-construction, so as to explore sub-vertical seepage from the alluvial aquifers, and c.) the change in water saturation up- and downstream to explore longitudinal seepage. In 2022 three profiles parallel to the dam wall were taken at each site. These included one downstream, one far enough upstream to avoid interference from metal reinforcement in the dam wall, and one 95 - 150 m upstream to be within the calculated range of sediment accumulation but at least 90 m from profile 2 to assess whether a difference was visible (Figure 5-4, (profiles 1-3 respectively)). One profile perpendicular to the dam wall in the middle of the riverbed (Figure 5-4, (profile 4)) was undertaken at all six sites (Appendix F). Profiles 1 and 2 were generally within 20 m of the dam wall to capture impact of seepage downstream and to compare near-dam wall conditions with those conditions far upstream in profiles 3 and 4. Two additional profiles were conducted at the mature sites in 2023 along the base of the riverbanks, perpendicular to the dam wall. These

were done to assess whether the nature of the subsurface along this boundary could help to suggest greater or lower levels of lateral seepage depending on the presence of unconsolidated sediments or unweathered bedrock respectively.

Profile locations were constrained by construction activities at new sites, as well as rock outcrops and roads. In 2023, these profiles were repeated at Kithunthi to assess reproducibility and at the new sites to compare differences pre- and post-dam construction. Surface water upstream of the dam walls at Wambiti and Kyakivandi in 2023 meant that perpendicular profiles could not extend upstream of the walls here.

Electrode positions in 2023 were re-located using GPS coordinates collected in 2022 with a GPSmap 62s, which has a GPS accuracy of <10 m, an altimeter

accuracy of ± 3 m, and a compass accuracy of $\pm 2^\circ$ (Garmin, 2010). Profile 5 located 500 m upstream was performed only at Kipico to assess whether water levels differ upstream of the accumulated trapped alluvium (that which has built up since dam wall construction).

Profile 4 used a 5 m minimum electrode spacing to give 200 m length perpendicular profiles of approximately 30 m in depth, apart from at Kyakivandi where wall construction activity forced two separate upstream and downstream profiles both 160 m in length. A 5 m minimum electrode spacing was initially used for profiles 1 - 3. However, on assessment of inversion profiles in the field, the electrode spacing was reduced to 4 m. This gave profile lengths of 160 m, which improved the vertical resolution of the data whilst still generally extending into the unweathered basement. IP data were collected alongside resistivity data at all of the 2023 profiles using the Schlumberger array. The Schlumberger and Gradient arrays gave similar resistivity inversion profiles. Whilst both were used to aid interpretation, the results report only the gradient arrays. All profiles are included in Appendix G.

To help in making the hydrogeological interpretations of the geophysical inversions, groundwater level measurements, probing, soil profiles, topographical profiles, geological observations, and irrigation surveys were undertaken:

- Water level measurements in scoop holes (dug during fieldwork or by water users (pre-existing)) were taken 400 m, 300 m, 200 m, 100 m upstream and 200 m, 100 m, and within 10 m downstream of the dam wall in the centre of the riverbed at all sites in 2023. Water level measurements were taken at intermediate locations in 2022. Six water levels were additionally taken in open agricultural wells, un-used hand-dug wells, and hand-dug pits in the riverbanks at Kithunthi (1), Kipico (1), Ngulai (2), and Kyakivandi (2). Water level measurements were surveyed in using a dumpy level, tripod, and staff, to an average vertical error of 20 mm.
- Probing, using a 4 m metallic rod was used to help in truthing the depth of the alluvial deposits at the ERT profile locations in the riverbeds.

- Scoop holes up to 3.4 m deep in the riverbed, analysis of fresh faces during wall construction in the riverbeds and riverbanks up to 5 m bgl, and augered or dug holes up to 2.2 m bgl in the riverbanks were used to obtain partial or complete weathered basement profiles. This included: composition, colour, grain size and sorting (estimated using a hand lens and grain size and sorting field estimation chart), density (measured using field techniques of thumb pressure for clay and finger penetration for sand), and dampness (classified as dry, damp, or wet) of each layer. Rock type and depth were noted when reached. Soil was classified based on the British Standard 5930:2015 'Code of practice for ground investigations' (The British Standards Institution, 2020). Scoop holes, augers, and dug holes were located according to the 2022 geophysical inversions, with the aim of explaining varying resistivity values seen in the inversions (Appendix H).
- Along each ERT profile, topography was collected using a handheld GPSmap 62s, and descriptions of the soil surface conditions at each electrode were made as above, aiding surface interpretations of the geophysics profiles.
- Geological observations were made on the composition of rock outcrops in and along the riverbed, including their degree of weathering.
- Irrigation surveys with five plot owners across four sites revealed where irrigation may have increased water content in the geophysics profiles for reasons other than rainfall or water loss from the dams. No irrigated agriculture was occurring at the other two sites. This survey gained ethical approval through CURES (CURES/17734/2023) (Appendix A). Surveys were conducted with the assistance of a translator at the sand dam sites. All plot owners were identified by talking to other users at the sand dams. Structured questions were centred around irrigation frequency, volume, and cultivated land area (Appendix I).

5.3.2.2 Literature review

Resistivity values from published studies for each of the layers found in the weathered basement were used to help in truthing the ERT inversions in this study (Table 5-1). Values of each material were taken from studies conducted in

basement aquifers with at least some gneiss due to its dominant presence in the study sites.

Table 5-1: Resistivity ranges of each material in a typical weathered basement profile reported in literature. The resistivity range (column 2) is the absolute minimum and maximum value found in literature. The resistivity quartile range (column 3) is the range between the first quartile of all of the minimum cited values and the third quartile of all of the maximum cited values in literature. Estimated aquifer characteristics and groundwater potential (ranging from poor to good) of saprolite and saprock from Anudu et al. (2014); and Ebong et al. (2021) are included. Values highlighted in grey represent saprolite and saprock of good groundwater potential in at least one of the two studies.

Material	Resistivity absolute range ($\Omega.m$)	Resistivity quartile range ($\Omega.m$)	References
Residual soil	7 - 10,000	30 - 1,075	(Adekoya et al., 2019; Adelusi et al., 2014; Aina et al., 1996; Aizebeokhai et al., 2010; Anudu et al., 2014; Bakundukize et al., 2016; Descloitres et al., 2008; Ebong et al., 2021; Elster et al., 2014; Jatau & Bajeh, 2007; Kayode et al., 2016; Kayode, et al., 2022; Kumar et al., 2016; Nyenje et al., 2022; Olayinka & Weller, 1997; Singh et al., 2019; Wekesa et al., 2020)
Saprolite (undefined water content)	4 - 3,500	15 - 848	(Adelusi et al., 2014; Aina et al., 1996; Aizebeokhai et al., 2010; Anudu et al., 2014; Descloitres et al., 2008; Ebong et al., 2021; Elster et al., 2014; Foppen et al., 2020; Jatau & Bajeh, 2007; Kayode et al., 2016; Kayode et al., 2022; Olayinka & Weller, 1997; Olorunfemi & Fasuyi, 1993; Zarate et al., 2021)
Saprolite (saturated)	7 - 700	19 - 586	Adekoya et al., 2019; Anudu et al., 2014; Bauman et al., 2016; Elster et al., 2014; Kumar et al., 2016; Nyenje et al., 2022)
	Saprolite aquifer characteristics and groundwater potential		
	<10	Clays: limited potential (Anudu et al., 2014; Ebong et al., 2021)	
	21-100	Optimum weathering: good potential (Anudu et al., 2014) Dominantly clay: poor potential (Ebong et al., 2021)	
	101-150	Medium conditions: medium potential (Anudu et al., 2014; Ebong et al., 2021)	
	151-300	Little weathering: poor potential (Anudu et al., 2014) Gravelly clay: good potential (Ebong et al., 2021)	
	>300	Negligible potential (Anudu et al., 2014; Ebong et al., 2021)	
Saprock	87 - infinity	175 – 2,979	(Adekoya et al., 2019; Aizebeokhai et al., 2010; Anudu et al., 2014; Descloitres et al., 2008; Ebong et al., 2021; Kayode et al., 2022; Kumar et al., 2016; Olayinka & Weller, 1997; Olorunfemi & Fasuyi, 1993; Wekesa et al., 2020; Zarate et al., 2021)
	Saprock aquifer characteristics and groundwater potential		
	<750	High fracture permeability: high potential (Anudu et al., 2014; Ebong et al., 2021)	
	750 - 1500	Moderately fractured: medium potential (Anudu et al., 2014; Ebong et al., 2021)	
	1500 - 3000	Fairly low effect of weathering: low potential (Anudu et al., 2014; Ebong et al., 2021)	
	>3000	Little or no weathering: negligible potential (Anudu et al., 2014; Ebong et al., 2021)	
Fresh bedrock	30 - infinity	600 – infinity	(Adekoya et al., 2019; Adelusi et al., 2014; Aina et al., 1996; Anudu et al., 2014; Bakundukize et al., 2016; Descloitres et al., 2008; Ebong et al., 2021; Groen et al., 2018; Jatau & Bajeh, 2007; Kayode et al., 2016; Kayode et al., 2022)

Resistivity values can vary greatly for several reasons. Higher resistivity in the regolith is often characteristic of dry, compact sand, gravelly sand, or laterite (Anudu et al., 2014; Kayode et al., 2022). Lower values can be associated with a combination of higher water, clay, mineral salt, soil organic content, or porosity (Anudu et al., 2014; Kayode et al., 2022; Nyenje et al., 2022). This makes it difficult to determine the most significant contributor to bulk resistivity. Lower resistivity values in the saprolite, for example, are partially determined by clay content, which tends to be higher in the upper saprolite. It can also be determined by water content, which can be higher in the lower saprolite if the upper saprolite is unsaturated (Anudu et al., 2014).

The resistivity of the saprock generally increases with depth as fracture density decreases as the occurrence of fluids decreases. Furthermore, fractures filled with water or decomposed clays from the saprolite can create heterogeneities in resistivity values in the saprock (Elster et al., 2014; Zarate et al., 2021). Finally, resistivities of fresh bedrock are greater than weathered rock (Shao et al., 2021), and can be impacted by mineral composition (Matsui et al., 2016). This is affected in part by the degree of metamorphism (Bakundukize et al., 2016). The resistivity of igneous and metamorphic rocks is generally higher than sedimentary rocks (Shao et al., 2021), whilst granite and gneiss can have similar resistivities and schist tends to have lower values (Bakundukize et al., 2016; Saad et al., 2012).

5.3.3 Data analysis

Raw data were cleaned in LS toolbox. Data points with a variance of >1% were removed, followed by any data points with a voltage of <0.0015 V, based on standard cleaning procedures (J. Adcock, personal communications, January 2022). A median of 2.9% of data points were removed from profiles. Data were inverted in Res2Dinv to give a resistivity section (Kayode et al., 2022). 'Bad data points' (i.e., those with very high, very low or negative apparent resistivities) were firstly exterminated. In the inversion settings a damping factor of 0.3 was used due to challenging electrode contact associated with the aridity of the ground (Loke, 1999). If the error obtained with a damping factor of 0.3 was high, a damping factor of 0.2 was tested and used if the error reduced. The robust-

constraint least squared method was chosen to avoid a smearing effect between the regolith and bedrock (Elster et al., 2014) and due to lower errors produced with this method. During inversion, the stop criteria was set with a 5% error reduction. A maximum of 6 iterations were carried out so that the difference between the model response and measured data was minimal but results were not unrealistic. Regular contour intervals were used for each profile, with a minimum of 5 $\Omega\cdot\text{m}$ and a maximum of 3000 $\Omega\cdot\text{m}$. This range was chosen based on Table 5-1. Any material >3000 $\Omega\cdot\text{m}$ is very likely to be fresh bedrock. Any material <5 $\Omega\cdot\text{m}$ is likely to be clay. The term 'low resistivity' was generally used for values <50 $\Omega\cdot\text{m}$.

The profiles were interpreted to show the water table and layer boundaries to indicate possible areas of saturation and depth to unweathered bedrock. Along each profile, each layer in the weathered basement was identified. The variable thickness of the saturated trapped alluvium was estimated using a combination of scoop holes, water levels, and probing. The horizontal extent and thickness of each of the weathered basement layers were estimated based on resistivity values in Table 5-1, water level and probing measurements, soil profiles, outcrop mapping, and IP data. No upper resistivity value of saprock could be identified as the boundary between this and fresh bedrock was not observed in the field. Combining these interpretations enabled the creation of modified conceptual models of sand dams and their surrounding aquifers, revealing the storage capabilities of sand dams, as well as seepage pathways into the weathered basement.

5.4 Results

Resistivity inversions supported by IP, surface observations, and literature provide insight into lateral and longitudinal seepage from sand dam alluvial aquifers into the surrounding weathered basement, indicating their level of hydrogeological interaction.

5.4.1 Geology of sand dams and their surrounding aquifer

The results from all six sites confirm that at least some of the trapped alluvium behind a sand dam wall is underlain by weathered basement material that is consistent with Figure 5-2. The resistivity and thickness ranges of the five layers (alluvium in the riverbed, residual soil in the riverbanks, saprolite, saprock, and fresh bedrock) are outlined in Table 5-2. The thickness of each layer varies along the river channel and between sites, indicating variable degrees of weathering of the underlying protolith, which can impact the water storage potential of sites.

5.4.1.1 Alluvium

Alluvium in the riverbed, in which the observed water table rests, varies in composition across a continuum of very loose - loose, moderately well sorted, medium - coarse sand. It is variably interspersed with silt, clay, and gravel layers. The mature sites are predominantly composed of moderately well sorted, coarse, slightly gravelly, silty sand. Pre-construction, Wambiti was predominantly composed of coarse sand, whilst the compositions at Nthonzweni and Kyakivandi were more variable, with more clay and fine - medium sand. The three mature sites have thicker deposits and greater upstream extents of saturated trapped alluvium than the new sites (Table 5-3). Silt, which typically settles at the end of the rainy season, was observed on the surface of all new sites post-construction.

5.4.1.2 Residual soil

Residual soil in the riverbanks varies in composition along a clay - loam - sand continuum, varying in density from soft - medium soft clay and loose - dense sand. At Kithunthi, Nthonzweni, and Kyakivandi, the residual soil is predominantly sandy, whilst at Kipico, Ngulai, and Wambiti, it is predominantly clay rich. The residual soil was only saturated at Kyakivandi (at 0.85 m and 1.2 m bgl).

Table 5-2: Resistivity and thickness ranges of each material observed in the ERT profiles. The resistivity studied range (row 2) is the absolute minimum and maximum values observed. The resistivity 1st and 3rd quartile (rows 3 and 4) are the first quartile of all of the minimum values and the third quartile of all of the maximum values respectively

		Geological layer						
		Residual soil	Unsaturated alluvium	Saturated alluvium	Unsaturated saprolite	Saturated saprolite	Saprock	Fresh bedrock
Resistivity ($\Omega \cdot m$)	Literature range (Table 5-1)	7 – 10,000	0.1-800		4-3500	7–700	87-infinity	30–infinity
	Studied range	5-836	5-3000	8-836	28-	12-1280	42-	152->3000
	1 st quartile of minimum	14	12	12	65	18	54	232
	3 rd quartile of maximum	467	763	356	-	587	-	3000
	Minimum thickness (m)	0.4	0	0	0	0	0	-
	Maximum thickness (m)	2	1.9	1.9	-	7.2	-	-

Table 5-3: Thickness of trapped alluvium at the wall and upstream extent of trapped alluvium and specifically saturated trapped alluvium (m) at each of the six sand dam sites based on measurements made in scoop holes and height of the dam wall

	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
Thickness of trapped alluvium at the wall (m)	2.8	2.75	3.3	0.22	1.16	0.66
Upstream extent of trapped alluvium (m)	320	350	250	240	200	200
Upstream extent of saturation in the trapped alluvium (m)	250	70	170	90	150	120

5.4.1.3 Saprolite

The alluvium and residual soil are underlain by saprolite. Observed during construction and in observation pits, it comprises soft - moderately stiff sandy clay - clayey silt - clayey sand, and sometimes contains eroded cobbles or boulders of bedrock. Red - orange iron oxide weathering, typical of saprolite, was observed during wall construction at Nthonzweni. The water table observed in the weathered basement was predominantly found here.

5.4.1.4 Saprock

The expression of the saprock is variable. Parts of the saprock easily lose surface fragments when brushed by hand, crumble in hand, or break when smashed with a hammer. Lower parts of the saprock appear unweathered to sight, being fairly resistant to breaking when hit with a hammer. Saprock of greater levels of consolidation is from deeper in the weathering profile, closer in characteristic to fresh bedrock (Figure 5-2). The fracture permeability of saprock enables some sub-vertical seepage from the overlying saprolite.

The walls at five of the sites: Kithunthi, Kipico, Ngulai, Nthonzweni, and Wambiti are predominantly constructed onto lower saprock (Figure 5-8a, c, d). This

interpretation is based on hard but slightly weathered rock being observed during wall construction at the new sites. It is also based on resistivity values indicative of saprock (around 232-356 $\Omega\cdot\text{m}$) at the known depths of wall construction at the mature sites. Some limited longitudinal seepage beneath the wall at these sites would therefore be expected.

5.4.1.5 Fresh bedrock

At depth, according to the resistivity profiles, saprock grades into fresh, unweathered bedrock, typically of negligible porosity and hydraulic conductivity (Figure 5-2). Kyakivandi appears to be the only site at which the wall is constructed onto fresh bedrock, observed in the field as unweathered, massive outcrops. Longitudinal seepage under this dam wall is therefore not expected to exist.

5.4.2 Lateral seepage

Lateral seepage has been defined as that flowing between the alluvial aquifers and weathered basement aquifers via the riverbanks when the water tables are hydraulically connected. Variations in resistivity and water levels between the riverbed and riverbanks can help indicate levels of potential lateral seepage from the alluvial aquifers into the adjacent weathered basement.

5.4.2.1 Geophysics

More extensive low resistivity material across the riverbeds and adjacent riverbanks is observed in the upstream compared to downstream profiles, the latter of which are outside the extent of accumulated trapped alluvium (Figure 5-5c). This is likely attributed to the greater saturated thickness of trapped alluvium upstream and a subsequently greater potential for lateral seepage. Very low resistivity values in the riverbanks at Kithunthi and Ngulai, however, may, in part, be attributed to clay (Figure 5-5b, Figure 5-6a). Whilst augering in the weathered basement at Kithunthi and Ngulai was limited to 2.1 m bgl, the topsoil and saprolite were variably composed of sand, silt, and clay. This supports that some, but likely not all, of the low resistivity signature here could be attributed to clay. Beyond the upstream extent of saturated trapped alluvium in profiles 3 and 5 at

Kipico there are very high resistivity signatures in the riverbed. This suggests an absence of saturated alluvium and therefore limited seepage compared to profile 2 just upstream. This is also supported by higher resistivity signatures in the immediate riverbanks, especially in profile 5. Whilst lower resistivity material is observed around the upstream extent of profile 4 (perpendicular to the dam wall) compared to just upstream, high IP signatures confirm that this is likely attributed to clay rather than water content (Figure 5-8d).

There is more extensive low resistivity material in the riverbanks in the upstream profiles at Kithunthi (Figure 5-6a) and Ngulai (Figure 5-5a, b) ($>8 \Omega.m$) compared to Kipico (Figure 5-6b) ($>28 \Omega.m$). This suggests higher water storage at the former two. Low resistivity signatures in the riverbed continue into both riverbanks at Kithunthi and Ngulai upstream, suggesting potential lateral seepage. This is not the case at Kipico, where the lowest resistivities are confined to the riverbed. Moderately low resistivity saprolite at Kipico suggests saturation. Whether or not this water content is a result of the sand dams is more difficult to conclude as the low resistivity signatures are not continuous with those in the riverbed. The augers in the riverbanks at Kipico up to 1.8 m bgl did not hit water and instead found weathered - slightly weathered bedrock. This suggests some potential impediment of shallow flow especially along the west bank (Figure 5-6b).

The perpendicular geophysical inversions along the base of the riverbanks at Kithunthi are characterised by low resistivity signatures. This is in comparison to those at Kipico and Ngulai which have some areas of much higher resistivity – indicative of unweathered rock. These signatures correspond to minimal rock outcrops observed at Kithunthi compared to greater outcrops at the latter two. This suggests that shallow lateral seepage at Kithunthi may be greater due to less obstruction from unweathered rock.

At the new sites there is slightly less low resistivity material in the riverbeds and adjoining riverbanks than at Kithunthi and Ngulai, but slightly more than was observed pre-construction. Less extensive low resistivity material in the weathered basement adjacent to the riverbeds at the new compared to the

mature sites may, in part, be attributed to less time elapsing since construction, allowing less lateral seepage.

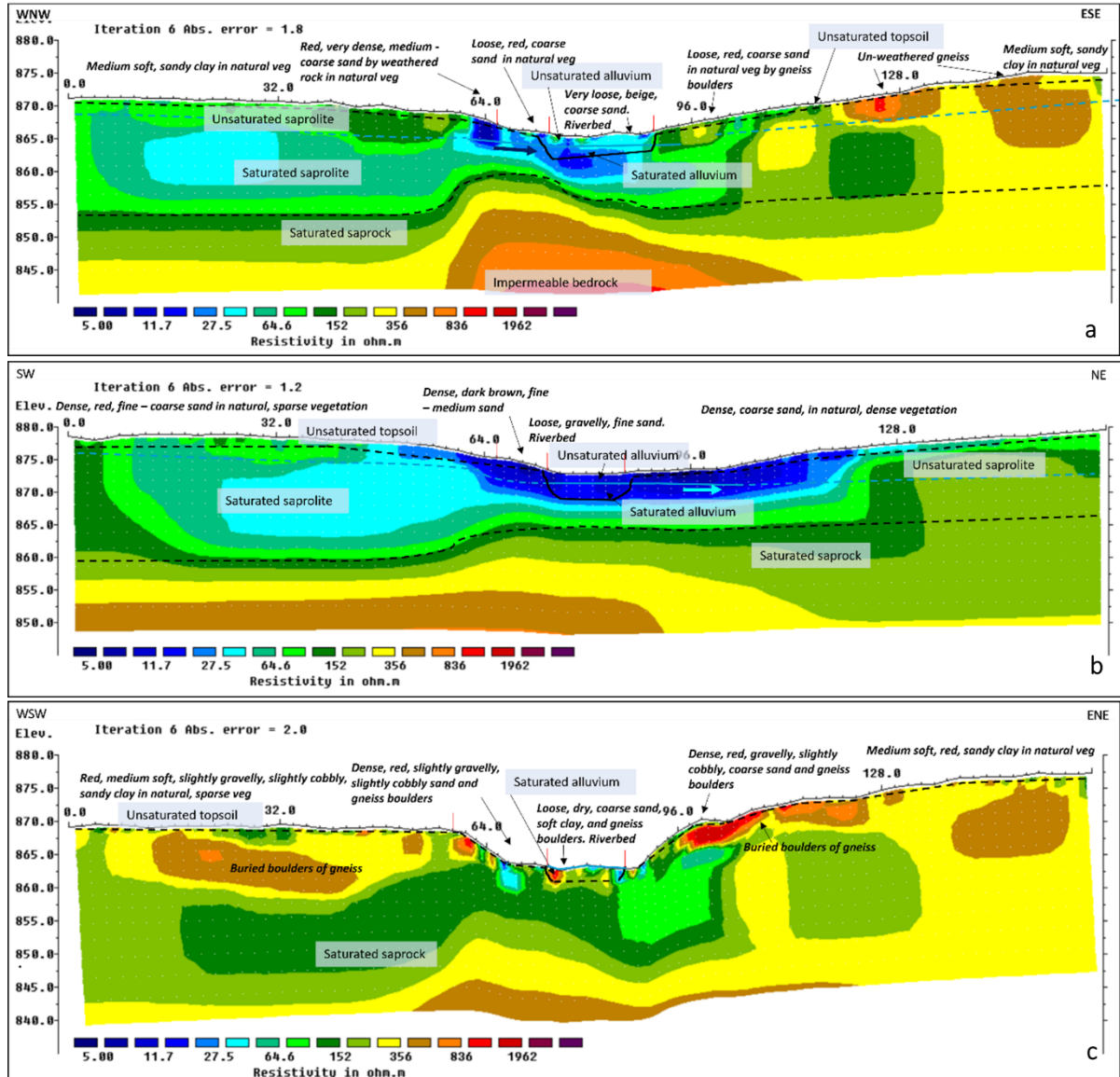


Figure 5-5: ERT profiles parallel to the dam wall at Ngulai 2022 (a) 9 m upstream, (b) 150 m upstream, (c) 13.5 m downstream. Profiles include surface observations in italics, with each change separated by red markers; observed and estimated layer boundaries in solid and dashed lines respectively (black for geological layers and blue for water table); and interpreted layers in boxes. Arrows indicate flow direction.

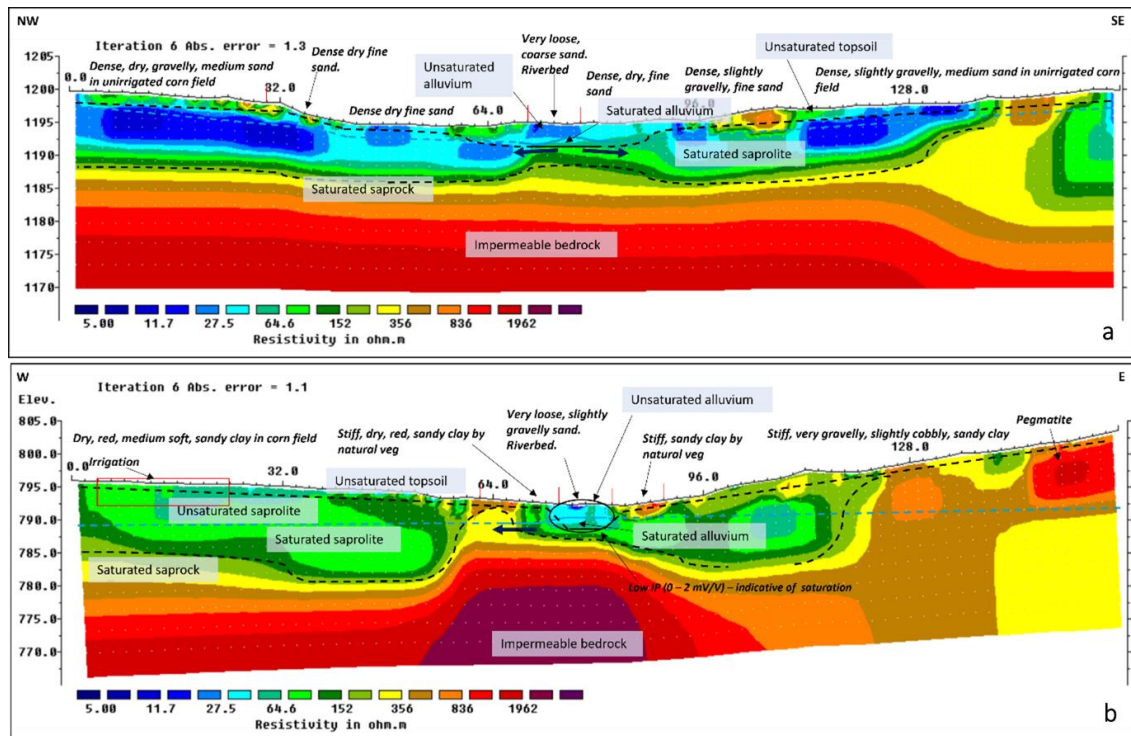


Figure 5-6: ERT profiles parallel to the dam wall at (a) Kithunthi 20 m upstream (2022) and (b) Kipico 9 m upstream (2022). Profiles include surface observations in italics, with each change separated by red markers; observed and estimated layer boundaries in solid and dashed lines respectively (black for geological layers and blue for water table); and interpreted layers in boxes. Arrows indicate flow direction.

5.4.2.2 Hydraulic gradients

Water levels elevations taken at Kithunthi (20 m upstream), Kipico (9 m upstream), Ngulai (150 m upstream), and Kyakivandi (45 m upstream) are higher in the centre of the riverbed as compared to those in the riverbanks. Horizontal hydraulic gradients (Appendix J) and therefore seepage away from the riverbeds exist as a result of the groundwater mound created by recharge of the alluvium (Figure 5-7). This is in comparison to Ngulai (9 m upstream), where the water level elevation in the riverbed is lower than in the riverbank, with a hydraulic gradient into the riverbed.

There are limited wells for water measurements in the riverbanks, with no water levels being available further than 17 m from the riverbed edge. No water level measurements are available at Nthonzweni or Wambiti. However, low resistivity

signatures in the inversion profiles at Kithunthi, Nthonzweni, and Wambiti close to the surface up to 70 m from the riverbed and at higher topographical gradients than the riverbed may indicate saturation and therefore a potential reversal of hydraulic gradient going back towards the riverbed (Figure 5-6a).

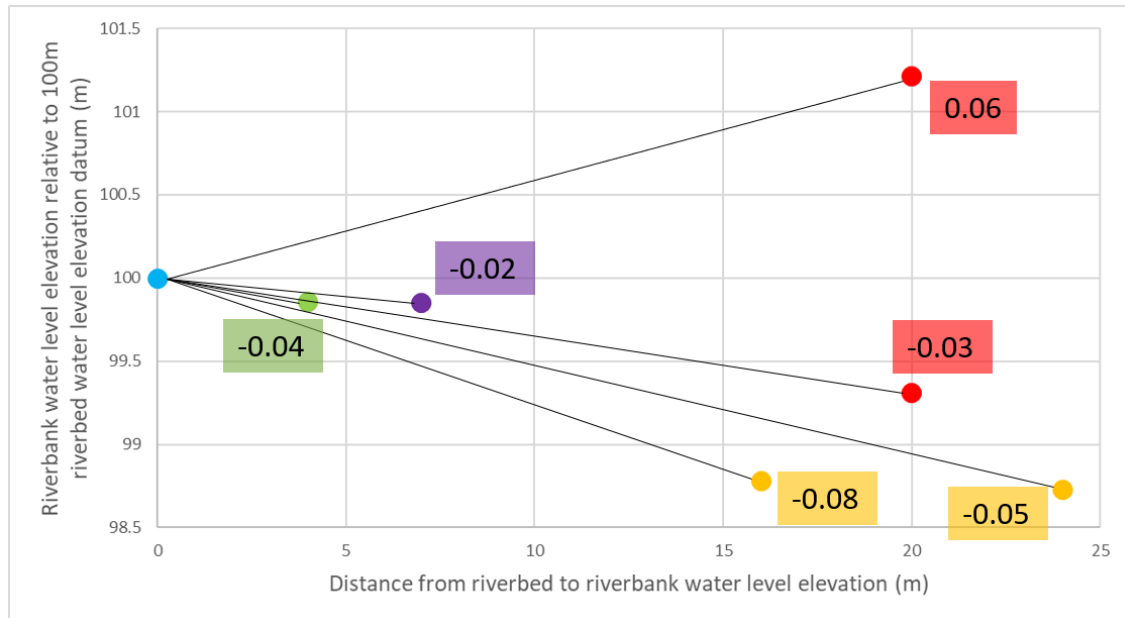


Figure 5-7: Riverbank water level elevations relative to a 100 m riverbed water level elevation datum taken at Kithunthi (green), Kipico (purple), Ngulai (red), and Kyakivandi (orange) upstream with the distance between the water level measurements in the riverbanks and riverbed (blue) along the x axis. Hydraulic gradients are in the coloured boxes next to each water level elevation.

5.4.3 Sub-vertical seepage

Sub-vertical seepage has been defined as the sub-vertical component of lateral loss from sand dams into the surrounding weathered basement aquifer via the base of the riverbed. This occurs whether or not the sand dam is connected to the water table in the weathered basement. Variations in resistivity beneath the alluvial aquifers, as a result of water content and geology, as well as water levels in the trapped alluvium help to suggest variable levels of potential sub-vertical water seepage from the alluvial aquifers into the underlying weathered basement.

5.4.3.1 Geophysics

When comparing inversion profiles pre- and post-construction at the three new sites, a slight decrease in resistivity is observed in and directly below the trapped alluvium (Appendix G). This is interpreted to be as a result of a slight increase in water content. This suggests some sub-vertical seepage into the weathered basement as a result of increased water storage in the trapped alluvium. Such a change was not observed in downstream profiles. This is supported by IP inversions. At Nthonzweni, in 2022, there was a high chargeability signature beneath the riverbed. In 2023 this signature was much lower and may suggest a slight increase in water content in the subsurface.

The resistivity of material underlying the alluvial aquifers varies between Wambiti (Figure 5-8a) and Kyakivandi (Figure 5-8b), and the other four sites. At the former two sites, the alluvium upstream of the dam wall is consistently underlain by saprock and bedrock of 152->3000 $\Omega\cdot\text{m}$ at 0-3.05 m bgl. This is observed in inversion profiles and in the field as outcrops of unweathered gneiss and schist in the riverbed. The change in resistivity values with depth is relatively sudden at these two sites. This indicates a relatively rapid change in basement properties over a small vertical distance. Resistivities in the crystalline bedrock can vary as a result of fracturing in the saprock. This is especially evident in the perpendicular profiles, (Figure 5-8a). This indicates some potential sub-vertical seepage from the alluvium into the crystalline basement at these sites. The parallel profiles conversely show more extensive, shallow fresh bedrock, indicating localised areas of impeded sub-vertical seepage (Figure 5-8b).

The alluvial aquifers at the four remaining sites, on the other hand, are consistently underlain by saprolite of 18 - 232 $\Omega\cdot\text{m}$ (Figure 5-8c-d). There is negligible unweathered rock observed in the riverbeds of Kithunthi, Kipico, and Nthonzweni. The change in resistivity values with depth at these four sites is generally more gradual than that seen at Wambiti and Kyakivandi, indicating a slower transition in basement properties and a greater depth of weathering. Higher potential sub-vertical water seepage from the alluvium into the underlying weathered basement is expected at these sites due to an absence of shallow

unweathered bedrock. The relative lateral homogeneity in the perpendicular profiles of these sites is interpreted to be as a result of continuously saturated saprolite and saprock. Low resistivity and a general absence of high IP signatures below the depth of alluvium, alongside field observations, suggests an absence of an impermeable very clay rich layer which would impede saturated flow (Figure 5-8c).

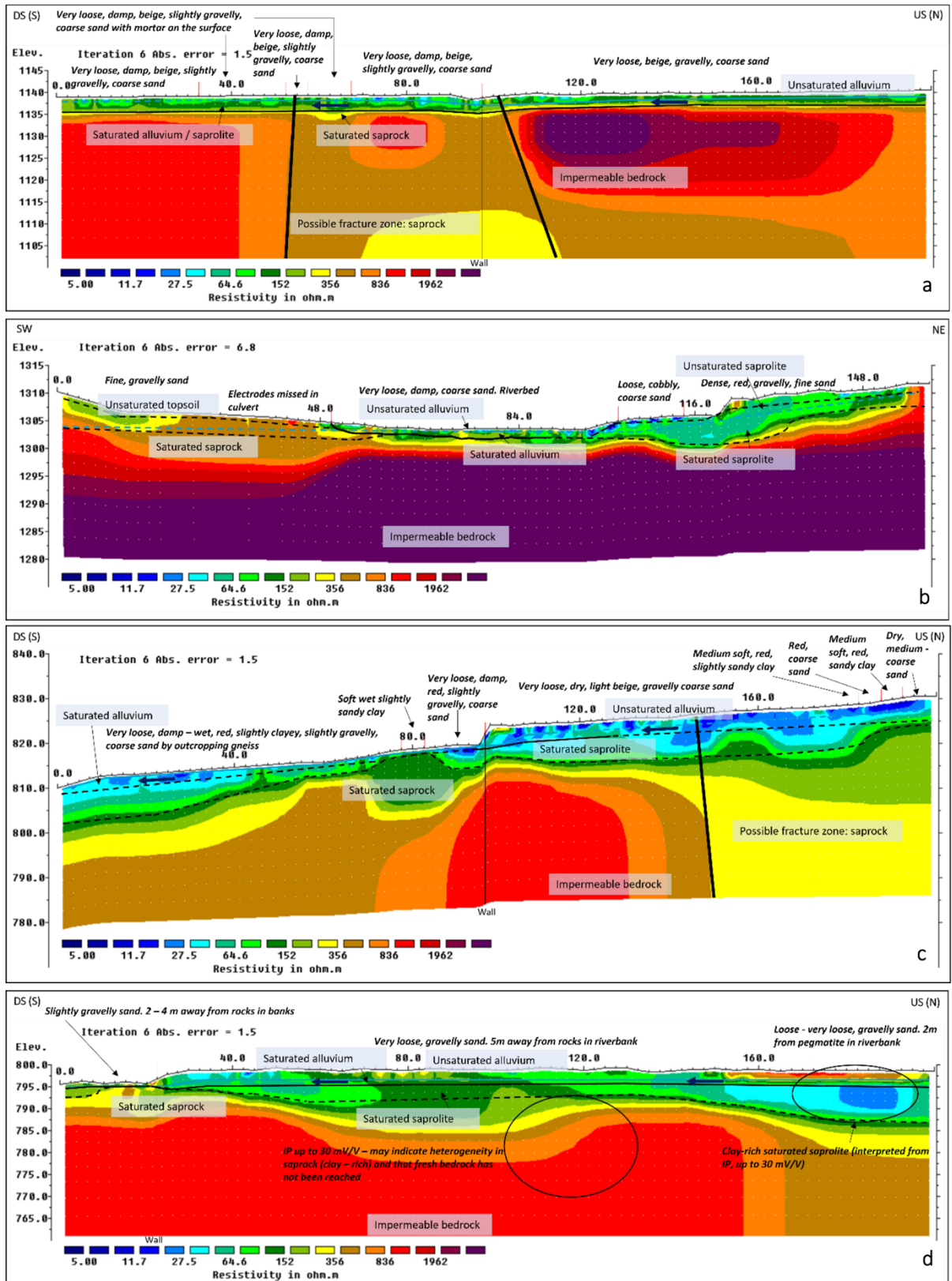


Figure 5-8: ERT profiles of (a) Wambiti perpendicular to the dam wall from downstream to upstream (2022), (b) Kyakivandi 140 m upstream parallel to the dam wall (2023), (c) Ngulai perpendicular to the dam wall from downstream to upstream (2022), and (d) Kipico perpendicular to the dam wall from downstream to upstream (2022). Profiles include surface observations in italics, with each change separated by red markers; observed and estimated layer boundaries in solid and dashed lines respectively (black for geological layers and blue for water table); and interpreted layers in boxes. Arrows indicate flow direction.

5.4.3.2 Water levels

The water levels in the alluvium get deeper further upstream at the new sites and Kipico. Conversely, at Ngulai and Kithunthi, the water levels are deepest at the wall. This is potentially due to handpump abstraction here, which was not occurring at the other four sites. Water levels are generally shallower and alluvium thinner at the new sites (Table 5-4).

Deeper water levels at Kipico and higher resistivity values in the regolith compared to other sites could be attributed to a lower water content in the regolith due to a faster rate of seepage into the surrounding aquifer. This may be due to greater hydraulic conductivity between the regolith and crystalline basement. Conversely, at Kithunthi and Ngulai, the measured water levels are comparatively shallower, and resistivity values comparatively lower, suggesting greater volumes of water stored in the regolith and a slower rate of seepage. This may be due to a lower hydraulic conductivity between the regolith and crystalline basement.

Table 5-4: Range of water depths (m bgl) from the wall to 400 m upstream at each site measured in 2022 (white) and 2023 (grey)

Distance upstream (m)		Mature sites						New sites					
		Kithunthi		Kipico		Ngulai		Nthonzwi		Wambiti		Kyakivandi	
	Year	22	23	22	23	22	23	22	23	22	23	22	23
10	Water depth (m bgl)	1.87	0.95	2.10	2.19	1.40	1.30		0.20	0.8	0		0
50		1.90							0.05	0.45		0.30	0
100		1.65	1.03	1.98	2.20		1.45	0.36	0.37	0.5	0.31	1.05	0.25
150		1.03				1.2	1.09		0.97	0.48		0.37	
200			0.66		2.30		1.07		0.45	0.9	0.32		0.36
300			0.60		2.30		0.92		0.48		0.51		0.55
400					2.84		0.95		1.15	0.55	0.47		0.51

5.4.4 Longitudinal seepage

Longitudinal seepage has been defined as that flowing under or around the dam wall from the upstream aquifer into the riverbed downstream. The difference in resistivity and water levels in the riverbed upstream and downstream of the dam wall can help indicate variable levels of potential longitudinal seepage from the alluvial aquifers.

5.4.4.1 Geophysics

At the three mature sites, greater thicknesses of low resistivity material (minimum of 5 $\Omega\cdot\text{m}$) are observed upstream compared to downstream. Downstream, low resistivity values are less extensive and reach a minimum of 12 $\Omega\cdot\text{m}$ (Figure 5-5, Figure 5-8c-d). This indicates increased water storage upstream and limited longitudinal seepage under or around the dam wall especially at Kithunthi and Kipico. Low resistivity material directly downstream of the dam wall at Ngulai in connectivity with that upstream suggests greater longitudinal seepage here, supported by field observations of surface water pooling up to 0.9 m deep on the downstream side of this dam wall.

At the new sites, pre-construction, low resistivity signatures (minimum of 8 $\Omega\cdot\text{m}$) were observed in the upstream and downstream riverbeds. Post-construction, more extensive and slightly lower resistivity material was observed upstream compared to downstream (minimum of 8 $\Omega\cdot\text{m}$ and 12 $\Omega\cdot\text{m}$ respectively). This is likely due to the thin build-up of water saturated alluvium upstream. The amount of low resistivity material downstream generally decreased post-construction, likely as a result of the dam wall reducing water flow downstream. This again indicates that the dam walls are leading to an accumulation of saturated alluvium upstream, whilst limiting longitudinal seepage to the downstream riverbed.

5.4.4.2 Hydraulic gradients

Water levels at each site are higher upstream compared to downstream (Appendix K), with hydraulic gradients in the alluvium existing in a downstream direction. This indicates the potential for longitudinal seepage beneath and/or around the dam wall at all sites, depending on the quality of the seal between the

dam wall and the bedrock and the degree of weathering of the bedrock. Hydraulic gradients downstream are greater than those upstream at all sites (Table 5-5). Assuming continuity of flow between up- and downstream of the sand dam, this increase may be due to a reduced cross sectional area of flow downstream, due to the reduced saturated thickness and/or riverbed width downstream. At Kyakivandi, where the base of the dam wall is constructed onto unweathered bedrock and therefore loss under the wall is concluded not to be occurring, groundwater loss around the sides of wall may be occurring. This is likely as bedrock was observed 3.7 m below the top of the wingwall, with part of the wingwall therefore being grouted onto weathered rock.

Table 5-5: Horizontal hydraulic gradients in the upstream and downstream riverbed at each site

	Kithun-thi	Kipico	Ngulai	Nthonz-weni	Wambiti	Kyakivandi
Up-stream hydraulic gradient	-0.004	-0.005	-0.008	-0.004	-0.002	-0.002
Down-stream hydraulic gradient	-0.013	-0.009	-0.017	-0.005	-0.003	-0.015

5.4.5 Revised conceptual sand dam model

The results help to conceptualise the studied sand dams and to answer the question of whether the alluvial aquifers are in hydraulic connectivity with the surrounding weathered basement (existing as MAR structures) (Figure 5-9a) or are shallowly underlain by unweathered bedrock (existing more as storage structures) (Figure 5-9b). The six studied sites appear to exist predominantly as MAR structures due to lateral seepage occurring at all sites. There are, however, some localised areas of greater storage where sub-vertical seepage is impeded. An additional model where the alluvial aquifer is directly surrounded by low permeability clay (existing as perched aquifers, as assumed in some literature) is included for comparison (Figure 5-9c).

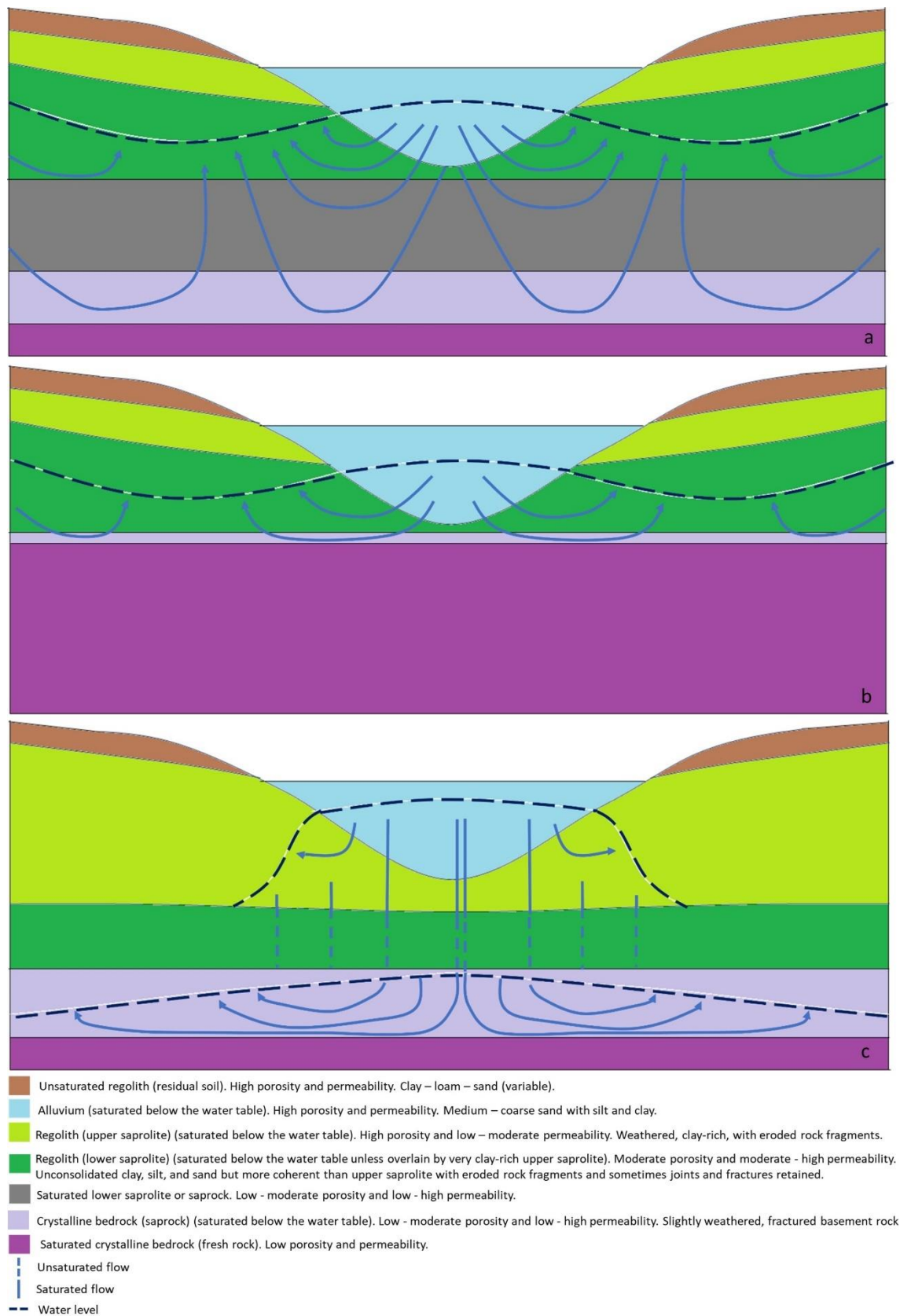


Figure 5-9: Conceptual models of a sand dam alluvial aquifer functioning as (a) MAR, (b) storage structures, and (c) perched aquifers

The available evidence suggests that sand dams exist along a continuum of connectivity with their surrounding aquifer, functioning predominantly as MAR structures (Figure 5-9a). Kithunthi, Kipico, Ngulai, and Nthonzweni were fully characterised as such. Greater hydraulic connectivity and subsequent seepage between the alluvium and surrounding weathered basement exist here. This is due to the alluvium being directly underlain by saprolite or saprock of low - high permeability, with deeper unweathered bedrock, and a connectivity between the water table in the alluvium and surrounding weathered basement. The low - moderate resistivity values of the saprolite and saprock, which gradually increase with depth, suggest a gradual change in the properties of the weathered basement, rather than a sharp no-flow boundary, as would be expected in the perched aquifer model (Figure 5-9c). Where riverbeds are underlain by thick layers of saprolite or saprock, water will be lost from the riverbed, recharging the surrounding layers to an extent. Such sites may be recognised pre-construction as having negligible unweathered rock in the riverbed as was the case at Kithunthi, Kipico, and Nthonzweni. Wambiti and Kyakivandi also show recharge behaviour across parts of the sites. Saturation was interpreted between the alluvium and underlying basement during the time of this study (mid-dry season). It is possible, however, that the inversion profiles and water level measurements would be different at different times of the year. At the end of the dry season, for example, if the water level has dropped below the base of the alluvial aquifer, the alluvium will no longer be in hydraulic connectivity with the underlying basement. An unsaturated layer would then exist.

Some of the sites (Wambiti and Kyakivandi) locally show characteristics of storage structures, with an impediment of sub-vertical seepage (Figure 5-9b). The existence of lateral seepage, however, means that a MAR function still somewhat exists. Figure 5-9b represents a more limited hydraulic connectivity, however, between the alluvium and surrounding basement due to the alluvium being underlain at shallow depths by unweathered bedrock. This could occur as a consequence of fluvial flows having eroded much of the saprolite and saprock. The alluvial aquifers at Wambiti and Kyakivandi are underlain by either fractured saprock or fresh bedrock, the former which will enable localised seepage. In

areas characterised as Figure 5-9b, lower sub-vertical seepage is expected than those characterised as Figure 5-9a due to the generally lower saturated thickness and hydraulic conductivity of the underlying material. Sites characterised as providing better storage potential may be recognised pre-construction as generally having more outcropping unweathered rock in the riverbed and riverbanks.

Some literature portrays sand dams as perched aquifers (Figure 5-9c). No studies have formally identified evidence of such classification of sand dams. Similarly, this work did not uncover evidence that any of the studied sites were behaving in this way. To the depth at which dug holes could assess the subsurface before collapse or water infiltration, there was no thick impermeable clay layer. Neither was there field evidence of a continuous low permeability layer beneath the alluvial aquifers underlain by an unsaturated layer. Having said this, due to an abundance of low resistivity material in certain profiles (Figure 5-5b and 5-6a) it is possible: a.) that a thicker clay layer exists beyond the depth of the dug holes and b.) for a thin, low permeability layer to not be apparent on the inversion profiles. At other sand dam sites, where a thick layer of clay may underlie and surround the alluvium, sub-vertical and extensive lateral flow may be impeded, enabling some sites to exist more like perched aquifers.

5.5 Discussion

More accurate conceptualisation of seepage from sand dams to the surrounding aquifer is important for maximising the potential impact that sand dams can have on small-scale sustainable water use in drylands (Eisma & Merwade, 2021; Ndekezi et al., 2023; Quinn et al., 2019; Trinchiera et al., 2018; Viducich, 2015). The integration of ERT and water level measurements provide, for the first time, evidence of the relative importance of lateral and longitudinal water seepage from the alluvial aquifers into the weathered basement. It does this by identifying areas of saturated weathered basement and the nature of material underlying the alluvial aquifers.

The results highlight the effectiveness of alluvial aquifers in ephemeral rivers across drylands as local recharge structures, whilst low resistivity values within

the upstream trapped alluvium indicates their storage potential. Whilst previous studies have found that focussed recharge can be substantial, (Constantz et al., 2002), diffuse recharge is generally concluded to be of greater importance in African drylands (Butterworth et al., 1999; Sorensen et al., 2024). For example, Sorensen et al. (2024) found that at one ephemeral stream, despite retention of water during the monsoon, focussed recharge was still relatively unsubstantial due to low permeability of the riverbed. This highlights that whilst sand dams and other similar structures from which water may be lost, such as check dams and infiltration ponds, can contribute to recharge, the contributed volume, especially due to the small-scale nature of sand dams is likely minimal.

The study also adds to the literature on the variable composition of weathered basement layers and indicate the appropriateness of using ERT in weathered basement groundwater studies and sand dam siting. The results have culminated in revised conceptual models of sand dams, highlighting the range of connectivity that exists between sand dam alluvial aquifers and the surrounding weathered basement.

5.5.1 Lateral seepage

Lateral seepage will likely occur at sand dams, especially at the start of the dry season when the groundwater mound in the alluvium has been replenished. The water level measurements (Figure 5-7) suggest there is generally a lateral hydraulic gradient from the alluvial aquifers into the adjacent weathered basement. This is generally consistent with the findings of Quinn et al. (2019), who conducted water balances at two of the mature sites in this study. They found one to lose water throughout the dry season, whilst the other initially gained water, before losing water around 1-month into the dry season.

Further from the riverbed, the low resistivity values at higher elevations (Figure 5-6a) may represent a reversal back to the natural hydraulic gradient towards the riverbed. This would be consistent with the findings of Borst & Haas (2006), Hoogmoed et al. (2007), and Strohschein, (2016). The lack of water level measurements further into the riverbanks limits this interpretation. Borst & Haas (2006) and Hoogmoed et al. (2007) monitored water levels in 21 piezometers in

the riverbed and riverbanks (up to approximately 30 m from the riverbed) in the dry season and found that heads in the alluvium were higher than those in the adjacent riverbanks. This resulted in lateral seepage from the groundwater mound (created from recharge in the alluvium) into the weathered basement until equilibrium was met. Groundwater heads further into the riverbank were found to be higher than those close to the riverbed, concluding that groundwater flow was orientated towards the riverbed outside the zone of influence of sand dams. Using modelling along the Kivuna and Kiindu rivers in Kitui, Kenya, Strohschein (2016) found that water in the riverbed seeped into the riverbanks under all simulated conditions (end of rainy season, after 50 dry days, after 100 dry days, and at the end of the dry season). However, under all conditions apart from at the end of the rainy season, at approximately 100 m from the riverbed, the hydraulic gradients reversed, with regional groundwater flow directed towards the river channel. Studies on check dams in India have found similar results. Mudrakartha (2003) and Palanisami et al. (2006) found that groundwater levels within 100 m of the studied dams rose to their maximum level within 48 days of the start of the rains, compared to up to 3 months for wells measured up to 400 m from the sites. The check dams had a greater reaching impact on the surrounding water table than has generally been conceptually modelled and measured at sand dams. The pattern of decreasing impact with distance is similar to that modelled at sand dams with larger hydraulic gradients found close to the riverbed, but on a much smaller scale with the aforementioned reversal back to the natural water table being met much sooner at sand dam sites. There is lower resistivity material in the riverbeds and riverbanks within the upstream extent of saturated trapped alluvium compared to downstream and beyond the upstream extent of saturation. This supports a hydraulic connection between the alluvium and weathered basement. This is consistent with what Hoogmoed et al. (2007) and Strohschein (2016) found. In the upstream alluvium they recorded higher groundwater levels in the riverbed compared to the riverbanks but higher levels in the riverbanks compared to the riverbeds downstream of the dam walls. This resulted in groundwater flows orientated towards the riverbanks and riverbeds, respectively.

Other results from the current study are less conclusive about the impact that the alluvial aquifers have on lateral seepage. The resistivity signatures in the riverbanks at the new sites have not extensively changed one year post-construction. Conducting a similar study on these sites several years after dam construction may aid in the interpretation of lateral seepage from the alluvial aquifers. Continuity of low resistivity material across the riverbed and riverbank was already seen at Wambiti pre- construction, where no trapped alluvium had accumulated. This may be due to seepage from the pre-existing riverbed. Furthermore, similarly low resistivity signatures are seen in the riverbanks of some of the new and mature sites and in the riverbanks upstream and downstream. This indicates that low resistivity signatures in the riverbanks are likely not solely as a result of saturation, and/or that saturation in the riverbanks is not solely as a result of lateral water seepage from the alluvial aquifers. These results highlight the challenges of ERT in investigating lateral water seepage, as other variables, (apart from just saturation) can influence resistivity signatures. Installing piezometers in the weathered basement is challenging and was not attempted in this study. However, with more time and resources, installing a series of piezometers in the riverbanks as Hoogmoed et al. (2007) did, and/or using environmental tracers would enable greater confidence in lateral seepage interpretations and improved conclusions regarding surface-groundwater interactions. Dashora et al. (2018) for example concluded that at one site there was no hydraulic connection between the surface and groundwater level because the infiltration rate did not diminish sharply during periods of high groundwater levels or rise quickly when levels declined.

5.5.2 Sub-vertical seepage

Water stored in the trapped alluvium behind the dam walls at each of the sites has produced alluvial aquifers, underlain directly by either saprolite, saprock or fresh bedrock. More sub-vertical seepage is expected to occur at sites continuously underlain by saprolite (as long as it is not very clay rich), as opposed to those underlain by predominantly fresh bedrock due to higher hydraulic conductivity at the former.

Some sub-vertical seepage is expected to occur at all of the studied sand dam sites through the underlying saprolite or saprock. Whilst saprock is typically permeable, its porosity is lower than saprolite, resulting in lower storage capacity but greater transmissivity than the upper saprolite, with evidence of ephemeral rivers losing water when underlain by saprock (Bakundukize et al., 2016; Kumar et al., 2016; Zarate et al., 2021). Upper saprolite typically has lower transmissivity, inhibiting flow if very clay-rich (Olorunfemi & Fasuyi, 1993). Such inhibition of flow does not appear to occur at any of the studied sites, with the observed saprolite not being exceptionally clay rich. The concluded absence of very clay rich upper saprolite below the riverbeds will enable some sub-vertical seepage of water from the alluvial aquifers at all studied sites in at least some locations. Having said this, low resistivity values suggest that clay-rich material does exist. Whilst more clay-rich material may be present at greater depths, unless this is continuous beneath the alluvium, some seepage will likely still occur.

Several ERT studies in crystalline basement terrain with similar inversion profiles to those in the current study have made similar interpretations based often on more constraining data (Aizebeokhai et al., 2010; Elster et al., 2014; Nyenje et al., 2022). Aizebeokhai et al. (2010) interpreted the lowest resistivity layers in their profiles as saprolite (4-50 $\Omega\cdot\text{m}$ and 1-100 $\Omega\cdot\text{m}$ respectively), being underlain by saprock (of higher resistivity than the saprolite but lower than the bedrock), with groundwater saturating both layers. Kumar et al. (2016) also identified weathered and fractured saturated granite up to 500 $\Omega\cdot\text{m}$. Finally, sub-vertical anomalies in inversion profiles observed by Groen et al. (2018), similar to Figure 5-8a were interpreted as fracture zones, which would allow sub-vertical seepage.

A study should be conducted once the new sand dams have reached maturity to collect water level measurements in the riverbed. This would help to confirm whether the water levels in the alluvium at sites characterised as Figure 5-9b (storage) are shallower than those at sites characterised as Figure 5-9a (recharge) due to lower levels of seepage. It would confirm whether lower levels of seepage are occurring at storage sites or whether areas of fracturing in the

saprock and lateral seepage are significant enough to enable equally high levels of seepage as sites characterised fully as MAR.

5.5.3 Longitudinal seepage

The results confirm that some sand dam walls are constructed onto slightly weathered saprock. This is consistent with the assumptions made by Eisma & Merwade (2021), Gezahegne (1986), Hut et al. (2008), Maddrell (2018), and Quinn et al. (2019). They hypothesised that sand dams are not always constructed onto unweathered material and, therefore, that some seepage under the dam wall is possible. Furthermore, longitudinal hydraulic gradients between upstream and downstream of the dam wall indicate the potential for longitudinal seepage at every site. However, the contrast in shallow resistivity values between generally lower resistivity signatures upstream and higher signatures downstream indicate that minimal longitudinal seepage is generally occurring. This is likely as a result of the dam walls impeding flow and effectively containing water.

5.5.4 Non-uniqueness of results

Relative levels of water seepage and associated saturation from the alluvial aquifers into the surrounding aquifer is one possible cause of the variable resistivity values observed at the different sites. However, other phenomena apart from water seepage can impact saturation, including rainfall and irrigation (Elster et al., 2014). The northern sites experience similarly high levels of rainfall, whilst the southern sites experience similarly lower levels (Figure 5-1). Yet overall lower and higher resistivity sites do not match this distribution of rainfall. Furthermore, no areas of irrigation correspond with the lowest resistivity signatures on the inversion profiles and are sometimes conversely associated with some of the highest resistivity values. These results indicate that no one factor alone can explain the variable resistivity signatures in the inversion profiles.

Furthermore, clay content, mineral salts, porosity, and organic content are other potential causes of low resistivity. Wekesa et al. (2020) found similar expressions of low resistivity material (10–15 $\Omega\cdot\text{m}$) in riverbanks as seen in Figure 5-5b and Figure 5-6a and interpreted these as clay-rich weathered basement, rather than

saturated. The results from this study and cross-comparison with other studies indicate the uncertainty when it comes to attributing resistivity signatures to water saturation and therefore the interpretation of seepage. IP and field observations can go some way to aiding the interpretation of the resistivity inversion profiles but without boreholes, uncertainty remains. Drilling a borehole in a future study at sand dams would allow a more accurate understanding of the composition of each layer and subsequent conceptual understanding of seepage. It would also enable borehole geophysics to be conducted. Despite this, the ERT profiles have provided a much more in-depth understanding of the subsurface below sand dams than has previously been available, valuably adding to the conceptualisation of how sand dams interact with their surrounding aquifer.

5.5.5 Recommendations

Whilst the ERT results alone are inconclusive as to the extent of water seepage due to the non-uniqueness of results, combined with field observations and literature, the inversions support the existence of some water seepage laterally and longitudinally at each site. Lateral seepage is seemingly the most notable seepage pathway. The results indicate the positive impact that sand dams can have on local water availability. By constructing dams shallowly underlain by unweathered basement, sub-vertical seepage will be reduced, hence enabling enhanced water storage in the alluvium. This model would favour abstraction by scoop holes in the alluvial riverbeds. The reverse is true for sites shallowly underlain by weathered basement, where more recharge to the surrounding aquifer is occurring. This model would potentially favour abstraction by deeper boreholes depending on hydrogeological conditions. Whilst lateral seepage in both models supports abstraction by handpumps constructed in the immediate riverbanks, sites underlain shallowly by unweathered basement would enable greater shallow storage here. Identifying sites along this spectrum during site selection would be useful in suggesting how the sand dam will behave. The findings show that a combination of simple surface observations and ERT can help to inform the most appropriate water abstraction method and ensure that sand dams are sited on hydrogeological conditions that match their desired

purpose: storage or recharge. This will help to maximise benefits that can be derived from the construction of a sand dam.

5.6 Conclusion

Combining ERT with water level measurements demonstrates the hydraulic connectivity between sand dams and the surrounding weathered basement. Through the development of conceptual models, it highlights the existence of variable lateral and longitudinal seepage from sand dam alluvial aquifers into the surrounding aquifer. The results suggest that the studied sand dams do not exist as perched aquifers or fully isolated storage structures as suggested in some literature but are generally in greater hydraulic connectivity with their surrounding aquifer. They increase local water storage in the surrounding aquifer as a result of lateral and longitudinal seepage from the alluvium and act as MAR structures, whilst still storing water within the alluvium. By using a combination of ERT and surface observations, it is possible to identify how potential sites for the construction of a sand dam may function along a spectrum of storage to MAR. Identifying which sites may lead to greater or lower levels of seepage is important for understanding how a sand dam will behave and what water resources will be available to local communities.

5.7 References

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6 Evidence and drivers of seepage from sand dams: insights from empirical evidence and modelling

6.1 Abstract

Dryland water harvesting structures on ephemeral rivers, such as sand dams, can perform storage and recharge functions. Whilst Chapter 5 suggests a local recharge function, the extent to which the resulting storage can meet water needs is debated. This study uses empirical data, flow rates derived from analytical models, and literature to provide evidence of variable longitudinal and lateral seepage, evaporation, and abstraction, adding to the findings in Chapter 5. This was assessed between six sand dams and their surrounding weathered basement aquifers across the short dry season. Lateral seepage was found to be the largest contributor to total loss. All sites lost some water, recharging the surrounding aquifer to a degree. However, all sites had sufficient water to meet abstraction needs in the short and long dry seasons, indicating their storage ability and resilience as dryland water management structures. Seepage was found to be most sensitive to riverbed and dam wall width, specific yield and length of alluvium, ΔH , and hydraulic conductivity and thickness of saprock under the dam wall. The results can be used to inform on site selection, construction criteria, remediation needs, and behaviour of water harvesting structures on ephemeral rivers in order to minimise or maximise seepage depending on the required purpose.

6.2 Introduction

Drylands are critical ecosystems. They are home to more than 38% of the world's population and contribute to about 40% of global net primary productivity (Maestre et al., 2012; Wang et al., 2022). Water scarcity, however, severely limits the livelihoods and ecosystem services that they can support (Právělie, 2016b). To try and cope with the increasing irregularity of surface water availability, dryland water management largely focuses on groundwater and water harvesting structures (Ruffino, 2009).

Water harvesting structures are often found on ephemeral rivers, which are common in drylands (Philipp & Grundmann, 2013; Wekesa et al., 2020). They include sand dams, rock detention structures, subsurface dams, and weirs (Gezahegne, 1986; Gooden & Pritzlaff, 2021; Hartley, 1997; Nilsson, 1988; Norman et al., 2022). Such structures usually comprise a rock or concrete retaining structure built perpendicularly to the riverbed and are designed to retain water in the rainy season for use in the dry season (Norman et al., 2022). Whilst this study is focused on sand dams, the findings are relevant to other water harvesting structures on dryland ephemeral rivers.

Water from sand dams can be lost laterally into the surrounding weathered basement aquifer (Borst & Haas, 2006a; Dashora et al., 2018; Gooden & Pritzlaff, 2021; Hut et al., 2008a; Parimalarenganayaki et al., 2015; Quilis et al., 2009; Quinn et al., 2019; Ruffino, 2009). Water can also be lost longitudinally under, around, or through the retaining structure depending on the quality of the retaining structure and presence of fractures in the underlying weathered basement (Aerts et al., 2007; Borst & Haas, 2006a; Eisma & Merwade, 2020). These losses reduce water volume in the trapped alluvium but can increase availability in the surrounding aquifer and downstream. Whilst seepage is difficult to estimate, Borst & Haas (2006), Ndekezi et al. (2023), Quinn et al. (2019) and Yifru et al. (2020) used modelling and water balances to estimate lateral seepage. Neufeld (2021) and Trincheria et al. (2015) also observed ponding, assumed to have resulted from longitudinal seepage.

Sand dams can serve one of two purposes depending on the nature of the underlying material: to trap and store water within the accumulated alluvium or to induce recharge to the surrounding weathered basement aquifer (Hartley, 1997). Current knowledge on what impacts seasonal water availability in sand dams is limited to models of a small number of fully-functioning sand dams (Borst & Haas, 2006a; Eisma & Merwade, 2020; Hoogmoed et al., 2007; Hut et al., 2008a; Quilis et al., 2009; Strohschein, 2016a; Viducich, 2015) or a catchment of multiple sand dams (Aerts et al., 2007; Jansen, 2007; Lasage & Verburg, 2015; Loon & Droogers, 2006). Models have focussed on which parameters impact storage and

sedimentation (Borst & Haas, 2006; Hoogmoed et al., 2007; Jansen, 2007; Quilis et al., 2009; Quinn et al., 2019; Strohschein, 2016; Viducich, 2015), rather than seepage. An improved understanding of the effect of seepage on the functioning of sand dams and what impacts such behaviour in dryland ephemeral rivers is important under a future predicted increase in challenges related to reaching and maintaining water security in drylands as a result of climate change (Stringer et al., 2021).

The aim of this chapter is to analyse the relative importance of each loss pathway from sand dams: lateral seepage, longitudinal seepage (under the wall), evaporation, and abstraction. This is done in order to better understand the interaction between sand dams and the surrounding weathered basement, aiming to add to the knowledge contribution provided by the geophysical inversions in Chapter 5. It seeks to understand the influence of different site and hydrogeological parameters on seepage and to subsequently evaluate the contribution that sand dams can make to water security. The findings from the study can be used to inform site selection and construction of water management structures on ephemeral dryland rivers to help ensure such structures meet their intended purpose of either storage or recharge.

6.3 Methods

6.3.1 Study area

The study took place at the same six sand dam sites in Makueni County at which geophysical investigations were undertaken (Figure 5-1). The northern sites (Kithunthi, Nthonzweni, Wambiti, and Kyakivandi) belong to the dry sub-humid regions, whilst the southern sites (Kipico and Ngulai) belong to the semi-arid regions (UNEP-WCMC, 2007).

6.3.2 Empirical data collection

Two field studies in Kenya were conducted in February - March 2022 and 2023 mid-way through the short dry season. The fieldwork involved empirical data collection, which has been used to assess evidence of lateral or longitudinal seepage at the six sites.

Several indicators, used to assess evidence of potential seepage at each site were identified based on previous studies (Cozens, 2017; Kitheka, 2016; Maddrell, 2018; Neufeld, 2021; Quinn et al., 2019; Trinchiera et al., 2015; van Haveren, 2004) and fieldwork observations. Each indicator was given a score from 1 - 4 at each site, increasing in likelihood of seepage. Each indicator was also ranked from 1- 6 at each site, increasing in relative evidence of seepage. Scores of likelihood and relative evidence of seepage were based on field observations and data collected. This was done in order to assess whether evidence of seepage was substantially different between lateral and longitudinal pathways and to highlight at which sites seepage was relatively higher and lower. This was done in order to validate model results (Table 6-1).

6.3.2.1 Hydraulic gradient between the trapped alluvium and weathered basement

Lateral hydraulic gradients between the trapped alluvium and weathered basement can be indicative of lateral seepage as water flows from higher to lower heads (Appendix J). This indicator was calculated by measuring water levels upstream of the dam walls in available agricultural wells, observations pits, or hand dug wells in the weathered basement riverbanks at six locations across four sites. Water levels at the same distance upstream in the saturated trapped alluvium at the start of the dry season were assumed to be at the surface of the alluvium (full saturation). At both Nthonzweni and Wambiti, where no water level measurements could be taken in the riverbanks, geophysics profiles were used to estimate the hydraulic gradient.

6.3.2.2 Vegetation health and density change in the riverbanks since sand dam construction

An increase in vegetation health and density in the riverbanks since construction can indicate lateral seepage as an increased availability of water in the riverbanks will allow a proliferation of vegetation. Vegetation interviews were conducted with sand dam users (Appendix L) and used to assess the extent to which the health and density of vegetation in the upstream riverbanks has changed between pre- and post-dam construction both close to and up to 100 m from the riverbed.

6.3.2.3 Composition of the riverbank base

Surveys along the base of the riverbanks on both sides of the trapped alluvium extending from the wall to 100 m upstream were carried out. The boundaries were assessed on percentage composition of slightly weathered and unweathered rock. This was done to provide a proxy for the near subsurface materials. Riverbanks with a higher percentage of rock are expected to allow less lateral seepage due to lower hydraulic conductivities.

6.3.2.4 Material onto which the wall is constructed

The nature and depth of the basement material onto which the dam walls are constructed can impact longitudinal seepage. Higher rates of longitudinal seepage are likely when walls are constructed onto unconsolidated material and when the thickness of weathered material is greater due to higher hydraulic conductivities and larger areas of flow respectively (Borst & Haas, 2006; Quilis et al., 2009). This indicator was assessed through interviews with sand dam construction crews and managers from ASDF (Appendix M), as well as observations of wall construction made during fieldwork and geophysical inversions using ERT (Appendix G). For full details of the ERT profiles see Chapter 5. The interviews in this study gained ethical approval through CURES (CURES/17734/2023 and CURES/17690/2023) (Appendix A).

6.3.2.5 Pooling water downstream of the dam wall

Pooled and running water downstream can be linked with longitudinal seepage under, around, or through the dam wall, whilst flow over the dam wall is associated only with pooled water (Neufeld et al., 2021; Trinchiera et al., 2015). To differentiate between these two origins of pooled water, the observed change in pooled water depth over time (across a period of between 15 and 29 days) was compared to the expected rate of open water evaporation in February of 6 mm/day, calculated by Kiptala et al. (2013), based on the Penman method.

Table 6-1: Framework for measuring evidence of potential lateral and longitudinal seepage from water harvesting structures on ephemeral rivers

Indicator	1	2	3	4
Lateral seepage (between the trapped alluvium and weathered basement)				
Hydraulic gradient between trapped alluvium and weathered basement (%)	0 - 5	5.001 - 10	10.001 - 30	>30
Change in vegetation health and density in the riverbanks from pre- to post-construction	No change in health and density of vegetation along the riverbanks between pre- and post-construction	Health and density of vegetation along the riverbanks have increased slightly directly adjacent the riverbed	Health and density of vegetation along the riverbanks have increased slightly directly adjacent and up to 100 m from the riverbed	Health and density of vegetation along the riverbanks have increased substantially directly adjacent the riverbed
Composition of the riverbank base	100% of the boundaries are composed of slightly weathered - unweathered rock	50 - 99% of the boundaries are composed of slightly weathered - unweathered rock	1 - 49% of the boundaries are composed of slightly weathered - unweathered rock	Neither of the boundaries are composed of any rock
Longitudinal seepage (under/around the dam wall)				
Material onto which the wall is constructed	Whole wall built on unweathered bedrock	Part of wall built on slightly weathered bedrock	Part of wall built on weathered bedrock	Whole wall built on weathered bedrock
Pooling water downstream of the dam wall	No pooled water or dampness	Damp sand but no pooled water	Pooled water after evaporation losses have been accounted for	Running water from under dam wall

6.3.3 Analytical modelling

A multi-reach water balance model was developed in which groundwater seepage into, through, and out, of the six studied sand dams were represented using Darcy's Law and a version of the resistance equation proposed by Dachler (Bouwer, 1978). This was done alongside abstraction and water table depth-dependant evaporation. Water levels observed in the weathered basement were assumed to be in hydraulic connectivity with those in the alluvium. This was due to shallow water table elevations in the weathered basement lying above the base of the river channel.

6.3.3.1 Model set up

Each site was divided into between two and four reaches of trapped alluvium upstream, depending on the number of water depth measurements taken within the trapped alluvium (Figure 6-1). This was in addition to one reach beyond the upstream extent of trapped alluvium and one reach downstream (Appendix N). The model was run on a daily time-step from 01.01.2023 - 15.03.2023 as an approximation of the short dry season, based on rainfall data (CHIRPS, 2021). At the start of the dry season, the alluvium was assumed to be saturated.

In each reach of trapped alluvium, the groundwater volume at the start and end of the short dry season was calculated based on the thickness, width, length, and specific yield of alluvium. This was compared to the groundwater volume pre-construction based on the volume of riverbed alluvium before the trapped alluvium accumulated. Dimensions were derived from geophysics profiles and field measurements. The change in water storage (m^3/day) in each reach was determined from the balance between inflows from the upstream reach and riverbanks, and outflows into the riverbanks and downstream reach and as evaporation and abstraction (Equation 1). Using a specific yield of between 0.07 - 0.35, derived from a range of literature values (Appendix O) and the plan area of each reach, the resulting change in head was calculated.

Each model was calibrated against measured water level elevations collected at each site approximately mid-way through the short dry season during fieldwork.

Calibration was done by altering the specific yield of the alluvium and the hydraulic conductivity of each material, as these parameters are recognised as uncertain and spatially variable (Appendix P). Model outputs were evaluated against telemetered handpump data from Ritchie et al. (2023) (Chapter 4) and seepage rates from Quinn et al. (2019) respectively.

Change in water storage

$$\begin{aligned}
 &= \text{Longitudinal flow out of reach} \\
 &- \text{lateral flow into the riverbanks} \\
 &- \text{evaporation} - \text{abstraction} \\
 &+ \text{longitudinal flow into reach} \\
 &+ \text{lateral flow from the riverbanks}
 \end{aligned}$$

Equation 1

Lateral flow between the riverbed and riverbanks in the reaches of trapped alluvium was calculated using Equation 2. Longitudinal flow into and out of each reach was calculated using Darcys Law. The water level elevations downstream and in the weathered basement riverbanks close to the riverbed were modelled to remain constant.

Evapotranspiration from the riverbank vegetation was accounted for within the lateral seepage component of the water balance. By using the crop coefficients of the four most common vegetation types observed (grass, trees, crops, and shrubs) and a potential evapotranspiration rate of 4.5 mm/day (Quinn et al., 2018), the actual evapotranspiration rate of each vegetation type was calculated. To account for soil moisture limitations, an estimate of the ratio of soil moisture to field capacity was used to estimate evapotranspiration from grass, crops, and shrubs, whose roots are assumed to lie above the water table. From this, the weighted actual evapotranspiration rate and subsequent volume lost across the riparian zone of each dam was calculated based on an estimation of the percentage cover of each vegetation type. The riparian zone area was based on the estimated upstream extent of trapped alluvium at each site and the width of 100 m, based on the maximum estimated lateral extent of impacts from a sand

dam. The volume loss was then calculated as a percentage of lateral seepage and total loss (Appendix Q).

Evaporation from the trapped alluvium was modelled to decrease linearly with depth from a potential rate of 4.5 to 0 mm/day when the water level was >0.7 m bgl (Quinn et al., 2018). Abstraction was accounted for in reach 1 at Kithunthi and Ngulai (as the only sites where handpump abstraction was occurring), based on telemetered data. Whilst telemetered data exists for Kithunthi, data used at Ngulai was an average from the 26 sites in Ritchie et al (2023). Further, to assess whether enough water was stored in each of the six studied sites to meet abstraction demand, the average and maximum abstraction values across the 26 sites across both the short and long dry seasons were integrated into each site's model. Due to higher abstraction rates, only data from 2021 were used in the analysis. This was to assess whether needs of a relatively higher abstraction year could be met.

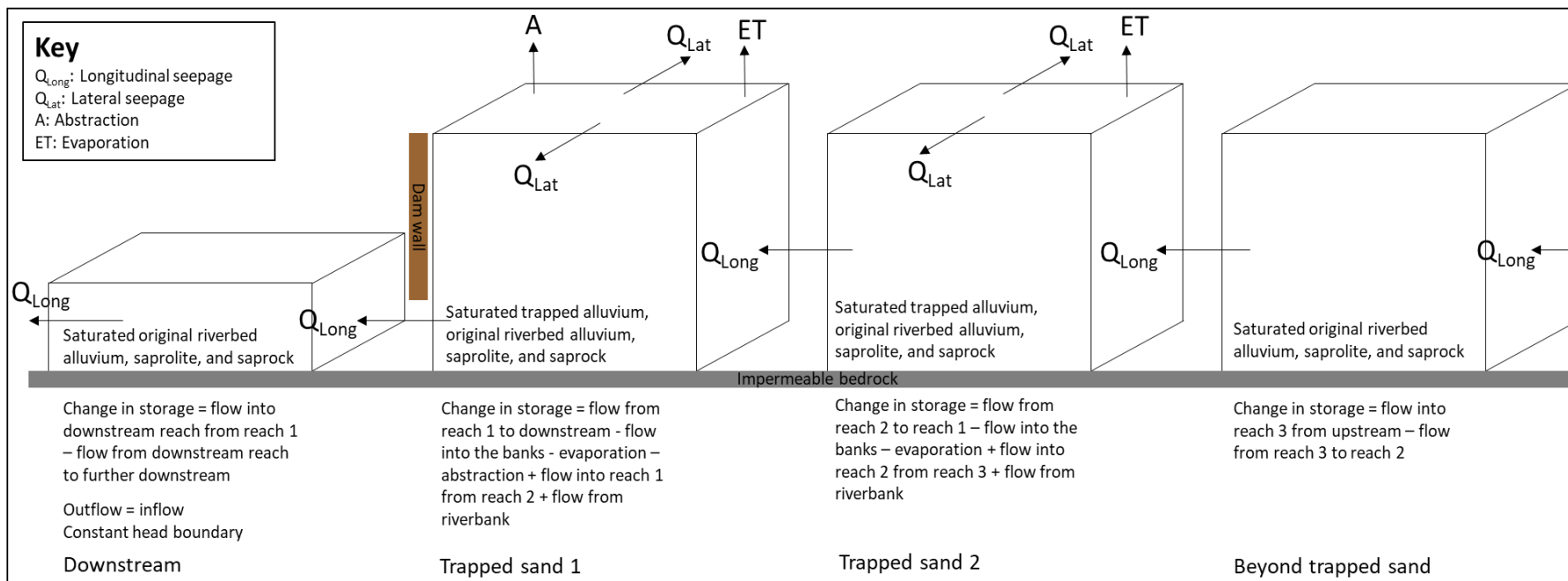


Figure 6-1: Conceptual model of flow through a sand dam. Each block represents an individual reach.

6.3.3.2 Lateral and longitudinal flow

Three basic soil conditions are distinguished in analysing seepage in river channels (Bouwer, 1978). Sand dams are most similar to the condition wherein material below a river channel is homogenous and underlain by material of much lower hydraulic conductivity, taken as impermeable in the analysis of the flow system (Bouwer, 1978) (Figure 6-2).

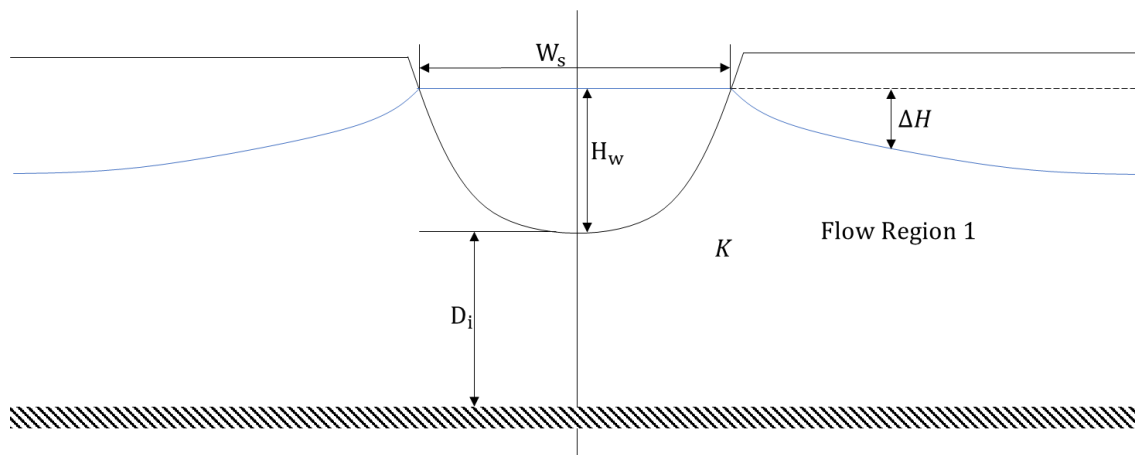


Figure 6-2: Geometry and parameters used in Equation 2 for a river channel underlain by impermeable material. Adapted from Bouwer (1969)

To account for high head loss in the region close to the riverbed, Dachler further divided the flow system in Figure 6-2 into two regions with curvilinear flow in region 1 (Bouwer, 1978). The equation for flow region 1 proposed by Dachler (Equation 2), was used to calculate lateral seepage from the sand dams. This was due to the close proximity of the water level elevations in the riverbank to the edge of the riverbed (maximum of 16m distant).

$$\frac{I_s}{K} = \frac{2F \Delta H}{W_s}$$

Equation 2

I_s = seepage rate (m^3/day)

ΔH = vertical distance between water level elevation in the riverbed and weathered basement riverbank (m)

W_s = width of riverbed at the surface (m)

K = thickness weighted hydraulic conductivity of the saturated weathered basement (m/s)

F = constant calculated by Equation 3 for shallow river channels

$$F = \frac{H_w + D_i - \Delta H}{H_w + D_i}$$

Equation 3

H_w = thickness of water saturated material in the riverbed (m)

D_i = depth from the base of the riverbed to the top of the unweathered bedrock (m)

I_s was multiplied by plan area of the riverbed as it is expressed as “the volume rate of water movement into the soil per unit length of channel and per unit width of the water surface in the channel” (Bouwer, 1978). ΔH was derived from water level elevations taken during fieldwork in the riverbed and weathered basement riverbanks where available or from geophysics profiles. W_s was derived from measurements taken during fieldwork. Hydraulic conductivity values for each material in the riverbed and weathered basement were taken from literature. Where a range of values in a single study were given, the mid-range was calculated, and the median of the mid-range taken (Appendix R). H_w was derived from a combination of probing and calculations, using the length of trapped alluvium, known height of trapped alluvium at the dam wall, and water depths. D_i was derived from a combination of site observations made during dam wall construction and geophysics profiles (Appendix G).

6.3.3.3 Sensitivity analysis

As uncertainties in parameter values are inevitable in groundwater studies (Rushton, 2003), a One-at-a-Time sensitivity analysis was undertaken across the short dry season at Kithunthi. The sensitivity of lateral and longitudinal seepage to hydrogeological, site, climatic, and human parameters was assessed. Kithunthi was chosen due to the presence of site-specific abstraction data. Parameters included were: specific yield of the alluvium, hydraulic conductivity and thickness of the alluvium and weathered basement layers, and ΔH (all hydrogeological), dam wall and riverbed width, and length of saturated alluvium (all site), evaporation (climatic), and abstraction (human). Each parameter was changed in 10% increments up to +100% and -100%. The absolute and percentage lateral and longitudinal seepage changes as a result of change in each parameter were calculated.

6.4 Results

6.4.1 Empirical evidence

6.4.1.1 Hydraulic gradient between the trapped alluvium and weathered basement

At each site, groundwater elevations in the riverbed were measured or estimated (from geophysics) to be higher than those in the weathered basement riverbanks at the start of the short dry season. This resulted in water table gradients away from the riverbeds of between 0.4 and 33%. This is as a result of the groundwater mound created by the recharge of the alluvium and indicates evidence of lateral seepage at each site in the case of hydraulic continuity between the water tables in the riverbed and riverbank.

6.4.1.2 Vegetation health and density change in the riverbanks since sand dam construction

Vegetation interview responses (Appendix L) reflect that there has been an increase in health and density of vegetation in the upstream riverbanks of the new and mature dam walls since construction. There could be other contributing factors to vegetation health and density. However, rainfall data indicates that total

rainfall in the season leading up to data collection was 1.6 - 1.8 times lower in 2022 - 23 post-construction of the new sites compared to 2021 - 22 (pre-construction) (CHIRPS, 2021). Whilst this has positive connotations for the local ecology, resulting higher rates of evapotranspiration may result in minimal increases in actually available water in the surrounding local environment.

At five of the sites (Kithunthi, Kipico, Nthonzweni, Wambiti, and Kyakivandi), vegetation is reported to have become greener and more abundant close to the riverbed. At Ngulai, more change, in the form of more abundant small trees, was reported further from the riverbed. At Kithunthi, Kipico, Nthonzweni, Wambiti, and Kyakivandi a slight increase in vegetation and/or greenness, especially of larger trees was reported further from the riverbed, apart from at Kithunthi where there was no change here. This suggests some, but not laterally extensive seepage from the trapped alluvium at most sites. At four sites (Kithunthi, Ngulai, Nthonzweni, and Wambiti), the abundance and greenness of vegetation downstream was reported to have minimally increased since dam construction, but far less than upstream, supporting lateral seepage from the upstream trapped alluvium. Overall, the most change was reported at Kyakivandi and the least at Wambiti.

6.4.1.3 Composition of the riverbank base

The composition of the riverbank bank at each site upstream of the dam wall (Appendix S) highlights that Kipico and Ngulai have the highest proportion of unweathered rock. They therefore may experience lower levels of shallow lateral seepage, compared to Kithunthi where no rock was observed. All sites were composed of <50% rock along the combined lengths of the upstream riverbanks on both sides of the riverbed, suggesting the potential for some lateral seepage at all sites. As these expressions of rock, shown by the ERT profiles, are not vertically continuous, deeper lateral seepage will likely not be impeded.

6.4.1.4 Material onto which the wall is constructed

Five of the dam and wing walls (Kithunthi, Kipico, Ngulai, Nthonzweni, and Wambiti) are constructed, predominantly, onto slightly weathered rock (saprock). Nthonzweni is also partly constructed onto weathered rock (saprolite), with

unweathered bedrock being >7.3 m beneath the wing walls. Terracing onto sand was subsequently used here due to time constraints to finish construction before the onset of the rains. Kyakivandi is the only site at which the wall is fully constructed onto unweathered bedrock, observed in the field as fresh bedrock.

The depth from the base of the dam wall to unweathered bedrock at the other five sites varies from 0.5 m at Wambiti to 8.9 m at Kithunthi. The interview responses (Appendix M) state that all of the fractures in the bedrock have been cleaned and filled in during construction with cement. Whilst this would limit shallow longitudinal seepage under the wall, it would not stop seepage at sites with thick expressions of weathered bedrock.

6.4.1.5 Pooling water downstream of the dam wall

A 0.9 m deep pool and running water downstream was observed at Ngulai in 2023. Pooling water downstream of the dam wall was observed at Nthonzwi and Wambiti (new sites) in 2023 post-construction, and at Kithunthi (mature site) in both years. Using an evaporation rate of 6 mm/day for surface water, the slow rate of reduction in size of the pools between the first and second depth measurements in 2023 indicated some replenishment and longitudinal seepage at all four sites. The measured change in pool depth was less than the expected change in pool depth at the second date of measurement if the pools were only being impacted by evaporation. The observed rates of change were less than 6 mm/day, suggesting that the pools had been replenished by seepage (Appendix T). The percentage difference between the measured pool depth ranged from 1.3 - 2.2% deeper than expected if only impacted by evaporation.

In addition to the aforementioned pooling, damp alluvium in a 4 m² area on the left hand side of the wall at Kipico and dryness across the rest of the wall suggests some longitudinal seepage under the left side of the dam wall that was being evaporated away each day. Dry conditions across the whole of the dam wall at Kyakivandi suggest no longitudinal seepage here.

6.4.1.6 Scoring of empirical evidence

Based on the evidence outlined above, each indicator has been scored (coloured 1 - 4) and ranked (1 - 6) at each site (Table 6-2). Simple descriptive statistics showed that average lateral score exceeds that of longitudinal, highlighting greater evidence of lateral seepage. The rankings indicate that Kithunthi showed the greatest empirical evidence of overall seepage and lateral seepage, whilst Ngulai showed the greatest evidence of longitudinal seepage.

Table 6-2: Scoring of each seepage indicator from 1 - 4 (increasing in likelihood of seepage) at each of the six sites. 1 - 6 indicate the least - most evidence of loss relatively at each site. LHS = left hand side, RHS = right hand side

	No data	1	2	3	4	
	Site					
	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
Lateral indicator						
Hydraulic gradient between trapped alluvium and weathered basement (%)	5	6	(LHS)	4	3	(LHS)
			1			2
			(RHS)			(RHS)
Vegetation health and density in the riverbanks	4	2	3	5	1	6
Composition of the riverbank base	6	1	2	3	4	5
Longitudinal indicator						
Material onto which the wall is constructed	5	3	4	6	2	1
Pooling water downstream of the dam wall	4	2	6	3	5	1

6.4.2 Analytical modelling

6.4.2.1 Temporal variability in loss

The measured and modelled water levels and evidence of loss show good alignment, with the results highlighting variability in storage and loss between each site and over time. There is an average derivation of only 0.1 m between measured and modelled water levels.

The simulated water table in the trapped alluvium fell, on average, by 15 mm/day. This resulted in lower rates of lateral and longitudinal seepage into the riverbanks and under the dam wall over time as ΔH decreased, whilst increasing rates of lateral seepage into the riverbed at locations where loss from the riverbed resulted in higher heads in the riverbank. Consequentially, the rate of water table fall between the start and mid-point of the short dry season (6th February) was higher (average of 31 mm/day) than that between the mid-point and end of the short dry season (average of 2.2 mm/day) (Figure 6-3).

Total lateral and longitudinal seepage from the alluvium decreased over time. Lateral seepage ranged from a daily minimum and maximum of 30 and 330 m³/day respectively at the start of the dry season to a daily minimum and maximum of 0 and 28 m³/day respectively at the end. Average daily lateral seepage rates from each site ranged from 23 - 73 m³. Estimates of the volume of lateral seepage lost to evapotranspiration from the riparian zone suggest volumes of between 7 and 33 m³ were lost daily, accounting for between 9 and 99% of lateral seepage across the whole short dry season at individual sites (Appendix Q).

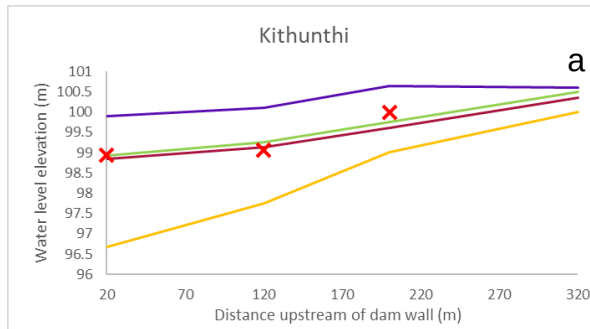
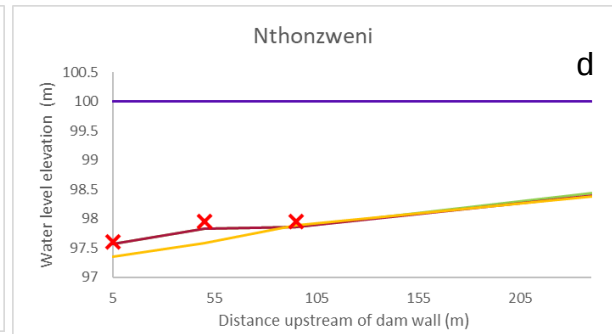
Longitudinal seepage was generally much lower and ranged from a daily minimum and maximum of 0.07 and 5.7 m³/day respectively at the start of the dry season to a daily minimum and maximum of 0.04 and 4.2 m³/day respectively at the end. At Kyakivandi longitudinal seepage stayed constant at 0 m³/day due to construction on fully unweathered bedrock. Average daily longitudinal seepage rates from each site ranged from 0 - 4.3 m³.

Evaporation rate from alluvium similarly decreased over time as the depth of water below ground level increased. Evaporation from bare sand at the start of the dry season occurred at the mature sites and Kyakivandi. Evaporation from surface water occurred at the new sites, with all of the trapped alluvium at Nthonzweni and Wambiti and part of it at Kyakivandi being covered by surface water. This was due to thin alluvium build up only one year post-construction. The rate of evaporation from bare sand ranged from a daily minimum and maximum of 13 and 23 m³/day respectively at the start of the short dry season. Evaporation reduced to 0 m³/day at the mature sites by the end of the season as water was >0.7 m bgl and ranged from 7.6 - 9.4 m³/day at the new sites.

6.4.2.2 Water balance

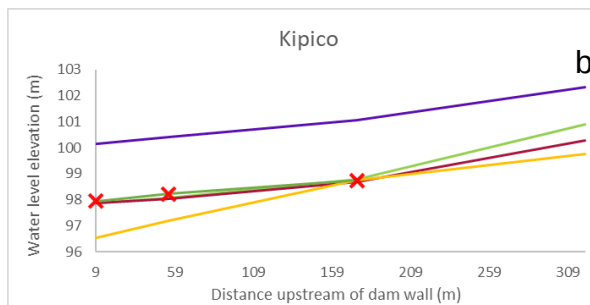
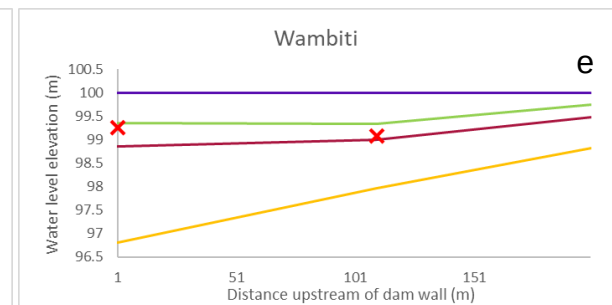
As evidence by Figure 6-3, storage declined at each site from the start to end of the short dry season as outflows exceeded inflows (Table 6-3). All sites lost water laterally and through evaporation. Five of the sites lost water longitudinally and two lost water by abstraction. Four sites also gained water from the weathered basement, albeit consistently in smaller simulated volumes compared to seepage into the weathered basement.

The water balance demonstrates the relative importance of lateral seepage at each site, accounting for between 57 and 97% of the total water loss, and the relative unimportance of longitudinal seepage and abstraction. This is supported by the empirical evidence which found lateral seepage to be more substantial than longitudinal. The greatest simulated lateral seepage at mature sites was at Kipico, due to a relatively large ΔH . This is supported by empirical evidence of the largest hydraulic gradient here. Other empirical evidence here (vegetation and riverbank base), however, suggests minimal seepage. Further, whilst the greatest simulated lateral seepage at new sites was at Wambiti, due to a large plan area of flow, this site had the least empirical evidence of lateral seepage.



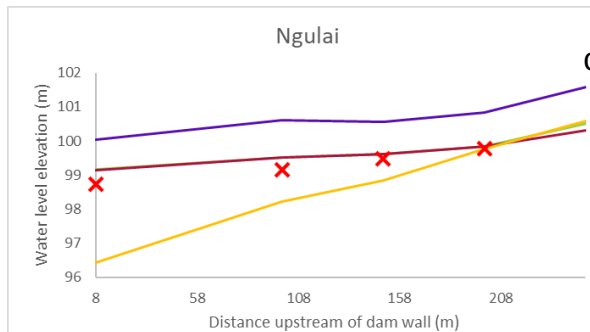
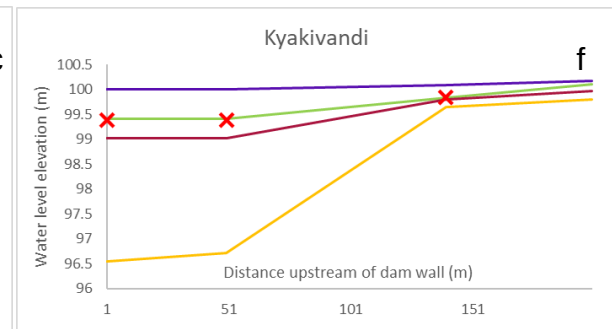
Rate of water table change (mm/day)

	20m	120m	200m	300m	5m	50m	95m	240m
T1-T2	-26	-23	-24	-2.7	-66	-59	-58	-42
T2-T3	-2.4	-3.4	-4.2	-3.6	-0.001	-0.01	-0.1	-1.1



Rate of water table change (mm/day)

	9m	55m	175m	350m	1m	110m	200m
T1-T2	-61	-64	-61	-39	-18	-18	-6.8
T2-T3	-0.3	-0.4	-2.4	-17	-13	-9.1	-7.1



Rate of water table change (mm/day)

	8m	100m	150m	200m	250m	1m	50m	140m	200m
T1-T2	-23	-29	-26	-27	-29	-16	-16	-6.9	-1.9
T2-T3	-0.5	-0.04	-0.01	-0.001	-5.7	-11	-11	-1.0	-3.5

— Simulated water level elevation 01.03.23 (m)

— Simulated water level elevation 15.03.23 (m)

✗ Measured water level elevation mid-point (m)

— Simulated water level elevation mid-point (m)

— Base of alluvium

Figure 6-3: Simulated water level elevations at the start (blue), date of data collection (approximate mid-point) (green), and end (maroon) of the short dry season in each upstream reach and measured water level elevations on the date of data collection (red cross) compared to the base of the alluvium (orange). (a) Kithunthi, (b) Kipico, (c) Ngulai, (d) Nthonzweni, (e) Wambiti, (f) Kyakivandi. Rate of water table change (mm/day) between the start of the short dry season and date of data collection (T1-T2) and between the date of data collection and end of the short dry season (T2-T3) are shown for each reach

Abstraction (solely from handpumps) and longitudinal loss accounted for a maximum of 1 and 12% of total loss respectively. Whilst abstraction from the alluvium was not occurring at the new sites, surface water, which was not included in the modelled abstraction estimate, was being utilised for agriculture. Longitudinal loss was generally lower than lateral due to flow through saprock of low hydraulic conductivity beneath the dam wall. Simulated longitudinal seepage from the mature sites was greatest at Ngulai due to a large D_i (depth from the base of the riverbed to the top of the unweathered bedrock) and from the new sites at Wambiti. This was due to sustained higher hydraulic gradients across the dam wall over time as a result of relatively small rates of water table fall upstream.

This was supported by relatively greater empirical evidence of pooling at both sites compared to other sites. Due to smaller areas of flow, simulated longitudinal seepage from the mature sites was similarly small at Kithunthi and Kipico, and at the new sites was smallest at Kyakivandi. These results at Kipico and Kyakivandi are supported by the least empirical evidence of longitudinal seepage here.

The contribution to loss that evaporation makes is highly influenced by the presence of surface water and the depth of water below ground level. Evaporation from bare sand at mature sites accounted for between only 2 and 12% of total loss. This compares to evapotranspiration, which was estimated to account for between 89 – 99% of the water lost to lateral seepage and 77 – 85% of total loss at mature sites (Appendix Q). At new sites, evaporation from bare sand and surface water was more impactful, accounting for between 20 and 43% of total loss, whilst evapotranspiration was estimated to account for between 9 – 63% of

the water lost to lateral seepage and 6 – 55% of total loss (Appendix Q). High rates of evaporation from surface water and the exposure of alluvium with shallower water tables once the surface water was lost, meant that evaporation was sustained until the end of the short dry season and was a greater contributor to loss at new sites in comparison to mature sites. This was in comparison to evapotranspiration, which was lower at new sites. This is likely in part due to slightly smaller riparian zones and lower overall vegetation cover across the riparian zones at new sites. Whilst there was some misalignment between the empirical and modelled data, the common finding of greater influence from lateral rather than longitudinal seepage and the good alignment between modelled results and pooling and hydraulic gradients help to validate the modelled results.

Table 6-3: Water balance for each site indicating inputs and outputs and subsequent change in water storage across the modelled period (01.01.2023 – 15.03.2023). All values are in m³. Values in brackets next to the site numbers indicate the estimated water storage capacity of each (mature) site when full. Values in brackets in the individual input and output rows indicate the pathway as a percentage of total input/output of each pathway. Values in brackets in the total input and output rows indicate the inflows/outflows as a percentage of total water storage capacity (of mature sites).

	Mature sites			New sites			Daily average
	1 (4,200)	2 (2,600)	3 (1,300)	4	5	6	
Input							
Q _{lateral}	0 (0)	0 (0)	2,200 (95)	380 (88)	110 (49)	460(86)	5.6
Q _{long}	160 (100)	620 (100)	110 (5)	50 (12)	110 (51)	75 (14)	2.5
Total input	160 (4)	620 (24)	2300 (177)	430	220	530	
Output							
Q _{lateral}	1,700 (86)	2,700 (97)	2,300 (85)	3,600 (79)	5,400 (63)	1,900 (57)	31
Q _{long}	3.8 (1)	46 (1)	320 (12)	50 (1)	70 (1)	0 (0)	1.1
Total seepage	1,700	2,800	2,600	3,600	5,500	1,900	
Evaporation	240 (12)	52 (2)	51 (2)	910 (20)	3,200 (36)	1,400 (43)	8.3
Abstraction	24 (1)	0 (0)	18 (1)	0 (0)	0 (0)	0 (0)	0.3
Total output	2,000 (48)	2,800 (108)	2,700 (208)	4,500	8,600	3,300	
Daily average	27	38	36	61	120	45	54
Storage change (total input – total output)							
Groundwater	1,800	2,200	400	230	430	110	
Surface water				3,900	7,900	2,700	

The volume of water lost and gained via each pathway changed over time, all decreasing, apart from inflow from the riverbanks (Figure 6-4). The rate of decrease in lateral seepage and evaporation and the rate of increase in inflow from the riverbanks slowed substantially over the dry season. Abstracted volume remained relatively stable over time, apart from one peak in February, which may have resulted from a high water demand for agriculture mid-way through the dry season. Longitudinal seepage volume remains low and stable, whilst inflow from upstream begins by increasing at the start of the dry season before quickly starting to decrease steadily. This is because of a larger water level difference between that in the alluvium and beyond the alluvium at the start of the dry season resulting in a larger hydraulic gradient.

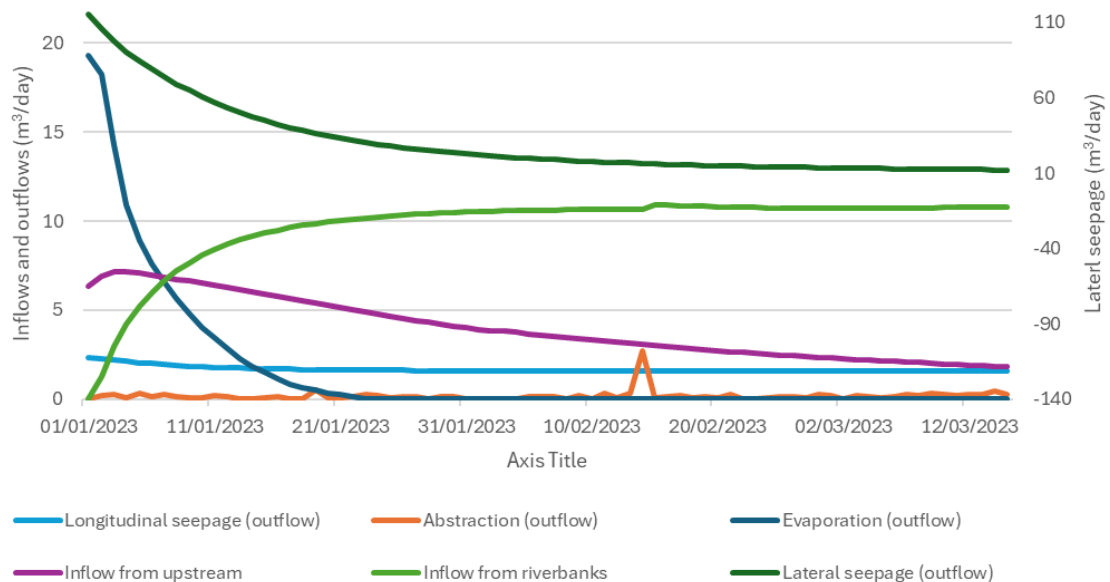


Figure 6-4: Short dry season average water balance time series at the three mature sites (Kithunthi, Kipico, and Ngulai), highlighting the change in the daily inputs and outputs to the model over time. Lateral seepage is on the secondary axis due to the substantial difference in magnitude compared to the other parameters

6.4.2.3 Water volume

The accumulation of alluvium post-dam construction naturally resulted in an increased volume of groundwater at the start of the short dry season compared to pre-construction. This estimated increase at mature and new sites was between 53 - 360% and 34 - 115% respectively.

At each simulated site there was water remaining in the saturated alluvium at the end of the dry seasons (Table 6-4). The groundwater volume was generally lower at new sites due to thinner alluvium build up, apart from at Wambiti, where the river channel is relatively wide. New sites would be expected to be fully filled with alluvium within several seasons, meaning that these lower volumes should not be a cause for concern in coming years. Groundwater volume estimates at the end of the long dry season were generally slightly less than at the end of the short dry season, as would be expected. The lack of substantial difference and slightly higher values at two of the new sites, however, was due to the longer duration of modelled inflow of water through the long dry season.

Table 6-4: Estimated groundwater volumes (m³) based on volume of sand and specific yields of 0.07 – 0.35 at each site at the start (without and with a sand dam) and end (with a sand dam) of the short and long dry seasons

	Kith-unthi	Kipico	Ngulai	Nthonz-weni	Wambiti	Kyakivandi
Groundwater volume at start of dry season without sand dam (m ³)	910	1,700	590	130	2,600	350
Groundwater volume at start of dry season with sand dam (m ³)	4,200	2,600	1,300	280	3,500	470
Groundwater volume at end of short dry season with sand dam (m ³)	2,400	390	900	59	3,100	360
Groundwater volume at end of long dry season with sand dam (m ³)	2,200	330	450	73	2,500	410

Overall, between the start and end of the short dry season, groundwater volume with a sand dam at the mature sites reduced by between 31 and 85% and at the new sites by between 11 and 79% (lost to seepage, evaporation, and abstraction). The reduction was generally smaller at the new sites due to loss of surface water. The smallest reduction from mature sites was at Ngulai due to substantially higher inflows here.

Using abstraction data from 26 sites from Ritchie et al. (2023), the median and maximum volumes of water likely to be required for abstraction from handpumps across the short dry season and therefore needed to be stored are 17.9 m³ (average of 0.2 m³/day) and 205.5 m³ (average of 2.8 m³/day) respectively. Each site was able to accommodate the median and maximum abstraction volumes, with water still being available in the alluvium at the end of the short dry season. Whilst abstraction from scoop holes was not explicitly included in this analysis, higher rates of potential abstraction were accounted for by using both the median (across the 26 sites) and maximum (at Woni 16) handpump abstraction volumes, the latter of which was substantially higher than the average from the 26 sites. Comparing median and maximum abstraction volumes to the volume of stored water in the alluvium at the start of the dry season at each mature site, a maximum of 1.4% (using the median abstraction of 17.9 m³) and 16% (using the maximum abstraction of 205.5 m³) was abstracted. The simulated results indicate that sites are able to provide for the abstraction needs of sand dam users under the modelled conditions.

Naturally, greater loss would be expected in the long dry season. Abstraction data from Ritchie et al. (2023) indicates a higher median and maximum abstraction of 47.6 m³ (average of 0.4 m³/day) and 743.2 m³ (average of 6.1 m³/day) respectively across this period. Running the models across the duration of the long dry season, under the same conditions as those used in the short dry season and accounting for maximum abstraction, sites had between 37 and 2,600 m³ of groundwater left by the end of the season. Table 6-5 highlights the higher input and output volumes across the long dry season. Whilst total loss across the whole season was slightly higher in the long dry season, average daily values were lower due to the longer duration of the season. The parameter showing the most substantial difference between the two seasons was abstraction, which from the two sites at which it was observed, was up to eight-times higher, due to the higher reliance of people on sand dams during this season. Despite the slightly higher levels of loss, these abstraction needs were still met. The availability of water by the end of the dry seasons was due to inflows of water from the riverbanks as soon as the head in the riverbed fell below that in the riverbank. This occurred at

faster rates under higher rates of abstraction. Generally, as losses to the downstream reach, abstraction, and evaporation exceeded inflows from the riverbanks, the water table in the riverbed continued to fall, but very minimally, meaning that water remained in the alluvium at each site.

Table 6-5: Water balance for each site indicating inputs and outputs and subsequent change in water storage across the long dry season. All values are in m³. Values in brackets indicate change compared to the short dry season (Table 6-3)

	Mature sites			New sites			Daily average
	1	2	3	4	5	6	
Input							
Q _{lateral}	9	0	3200 (*1.5)	760 (*2)	530 (*4.8)	760 (1.7)	5.4
Q _{long}	240 (*1.5)	710 (*1.1)	280 (*2.5)	50 (*1)	270 (*2.5)	120 (*1.6)	2.4
Total input	250 (*1.6)	710 (*1.1)	3500 (*1.5)	810 (*1.9)	600 (*2.7)	880 (*1.7)	
Output							
Q _{lateral}	1,800 (*1.1)	2,900 (*1.1)	4,000 (*1.7)	3,600 (*1)	6,300 (*1.2)	2,600 (*1.4)	19
Q _{long}	15 (*3.9)	51 (*1.1)	210 (*0.6)	29 (*0.6)	51 (*0.7)	0	0.4
Total seepage	1,800 (*1.1)	3,000 (*1.1)	4,200 (*1.6)	3,600 (*1)	6,300 (*1.1)	2,600 (*1.4)	
Evaporation	240 (*1)	52 (*1)	80 (*1.6)	1,300 (*1.4)	4,600 (1.4)	2,200 (1.6)	8.4
Abstraction	190 (*8.0)	0	48 (*2.3)	0	0	0	1.0
Total output	2,000 (*1)	3,000 (*1.1)	4,300 (*1.6)	4,900 (*1.1)	11,000 (*1.3)	4,800 (*1.5)	
Daily average	18 (*0.7)	25 (*0.6)	36 (*1.0)	41 (*0.7)	90 (*0.8)	40 (*0.9)	28
Storage change (total input – total output)							
Groundwater	2,000 (*1.1)	2,300 (*1.0)	850 (*2.1)	210 (*0.9)	1,000 (*2.3)	60 (*0.5)	
Surface water				3,900 (*1.0)	9,300 (*1.2)	3,900 (*1.4)	

6.4.2.4 Sensitivity analysis

Table 6-6 illustrates the impact that variations in parameter values had on total lateral and longitudinal seepage across the short dry season.

Riverbed width, length and specific yield of alluvium, and ΔH had the greatest impact on lateral seepage. A 100% increase in all four parameters resulted in a 102, 91, 89, and 89% increase in total lateral seepage respectively across the short dry season. Dam wall width and hydraulic conductivity and thickness of saprock under the dam wall had the most substantial impact on longitudinal seepage. A 100% increase in all three resulted in a 99 - 100% increase in total longitudinal seepage across the short dry season.

Potential evaporation rate had minimal impact on lateral and longitudinal seepage, with a 100% increase and decrease resulting in a maximum decrease and increase in lateral seepage of 3% respectively. Having said this, evaporation is highly impacted by water depth, which, in the models, increased relatively quickly due to seepage. Abstraction rate also had minimal impact on seepage, with a 100% increase and decrease resulting in a decrease and increase respectively in lateral (2%) and longitudinal (0.1%) seepage.

Seepage was relatively sensitive to the hydraulic conductivity of alluvium in the riverbed and soil in the riverbank. A 100% increase and decrease in K of the alluvium resulted in a 7% increase and 18% decrease in lateral seepage. A 100% increase and decrease in K of the soil resulted in a 0.7% increase and 6% decrease in lateral seepage and a 1% decrease and 5% increase in longitudinal seepage.

Finally, seepage was relatively sensitive to the thickness of alluvium in the riverbed, and soil in the riverbank. A 100% increase and decrease of alluvium thickness resulted in a 9 and 7% increase in lateral seepage. A 100% increase and decrease in soil thickness resulted in a 0.7% increase and 6% decrease in lateral seepage and a 1% decrease and 5% increase in longitudinal seepage.

Table 6-6 Results from sensitivity analysis at Kithunthi. Percentage change in daily lateral and longitudinal seepage when each parameter is changed by +100, +50, -50, -100% compared to modelled reference seepage rates (m³/day). Shows the highest impact on lateral seepage to be specific yield of the alluvium, riverbed width, saturated alluvium length, and ΔH , and on longitudinal seepage to be K of saprock in the riverbed, thickness of saprock under the dam wall, and dam wall width.

		Lateral seepage change (%)				Longitudinal seepage change (%)			
		100	50	-50	-100	100	50	-50	-100
Changed parameter	Potential evaporation rate (mm/day)	-3.0	-1.8	1.0	2.5	-0.1	-0.05	0.05	0.2
	Abstraction rate (m ³ /day)	-1.6	-0.8	0.8	1.6	-0.1	-0.1	0.1	0.1
	Specific yield of alluvium	88	44	-49	N/A	2.2	1.1	-1.1	N/A
	K alluvium riverbed (m/s)	6.5	3.8	-7.3	-18	0.7	0.3	-0.3	-0.6
	K soil riverbank (m/s)	0.7	0.3	-1.8	-6.4	-1.0	-0.6	1.3	5.4
	K saprolite riverbed (m/s)	0.3	-0.02	-0.9	-1.5	-0.5	-0.3	0.4	0.8
	K saprock riverbed (m/s)	-2.0	-1.2	0.4	1.2	100	50	-50	-100
	Thickness alluvium riverbed (m)	9.0	6.0	-16	7.0	1.1	0.6	-0.5	-0.6
	Thickness soil riverbank (m)	0.7	0.3	-1.8	-6.3	-1.0	-0.6	1.3	5.3
	Thickness saprolite riverbed (m)	-0.2	0.1	-0.6	-0.7	-0.02	-0.01	0.02	0.04
	Thickness saprock under wall (m)	-1.8	-0.9	0.9	1.8	100	50	-50	-100
	Thickness saprock riverbed (m)	-0.2	-0.3	-0.6	-0.9	-0.1	-0.03	0.05	0.2
	Thickness saprolite riverbank (m)	-1.0	-0.8	0.2	0.6	0.5	0.3	-0.4	-0.9
	Thickness saprock riverbank (m)	-1.5	-1.0	0.2	0.8	1.0	0.5	-0.5	-1.1
	Dam wall width (m)	-1.8	-0.9	0.9	1.8	100	50	-50	-100
	Riverbed width (m)	100	51	-52	N/A	2.9	1.4	-1.4	N/A
	Saturated alluvium length (m)	91	46	-50	N/A	-0.1	-0.1	0.3	N/A
	ΔH (vertical distance between water level elevation in riverbed and riverbank (m))	89	43	-41	-84	2.7	1.3	-1.1	-2.2

6.5 Discussion

Sand dams can be constructed to maximise storage or recharge. This study supports Eisma & Merwade (2021); Gezahegne (1986); Hut et al. (2008), Quinn et al. (2019), and the results from Chapter 5 in concluding that all studied sand dams lose some water into the weathered basement. Sand dams, therefore, partly provide a recharge function. The largest proportion of water lost was attributed to lateral seepage, whilst loss attributed to the other three pathways was relatively less substantial. Furthermore, the ability of sand dams to store water and thus provide for the needs of water users was evidenced by water availability at each site by the end of the short and long dry seasons.

6.5.1 Loss pathways

The water balance performed at each site indicates spatial and temporal variability in the magnitude of lateral and longitudinal seepage, evaporation, and abstraction. Average daily lateral seepage was 31 m³/day, similar to Yifru et al. (2020) who calculated a leakage of 34 m³/day. Average daily water table fall from the alluvium was 15 mm/day, which is very similar to values from Ndekezi et al. (2023) who, using pressure transducers to measure temporal changes in water levels, measured mean water table fall from three sand dam sites to range from 5.35±11.94 to 6.79±17.15 mm/day. This varies to findings from Quinn et al. (2019), who calculated a maximum rate of fall of 3.7 mm/day near the beginning of the long dry season. The higher rate in the current study is highly skewed by high seepage in the first 10 - 20 days, with an average daily water table of only 6.9 mm/day after the first 10 days. The initial water level in the alluvium from which the rate of fall is recorded by Quinn et al. (2019) was not at the surface. This indicates that either some water had been lost before the initial measurement or that the alluvium was not fully saturated at the start of the dry season. Quinn et al. (2019) modelled the long dry season, after the long rains, whereas the current study focussed on the short dry season after the short rains, in which a greater proportion of annual rainfall is received (Gichuki, 2000). It is therefore possible that greater water volumes occur at the start of the short dry season.

The study found that lateral seepage (of which evapotranspiration accounted for the majority at four of the studied sites), was the largest contributor to total loss across the short dry season, followed by evaporation from the alluvium, longitudinal seepage, and abstraction. Eisma & Merwade (2020), similarly found evapotranspiration to be the largest contributor to total loss. Eisma & Merwade (2020) modelled baseflow-groundwater runoff to account for 1 - 2%, evapotranspiration to account for 65 - 88%, and abstraction to account for 10% of total water loss across a year. This is similar to the current study in which evapotranspiration accounts for between 77 and 85% of total loss at mature sites. A potential evaporation rate of 4.5 mm/day was adopted in the current study from Quinn et al. (2018). This is in line with that used by Eisma & Merwade. (2020) and Ndekezi et al. (2023) (4.5 - 4.9 and 4.1 - 4.4 mm/day respectively). Whilst the change in potential evaporation rate with depth is based on results from Quinn et al. (2018) at one site, in reality, this will likely vary between and across sites depending on the level of shading and composition of the alluvium. Having said this, the sensitivity analysis demonstrated that seepage is not very sensitive to changes in potential evaporation when water depth increases as it does in the models. This is supported by Quinn et al. (2019) and Borst & Haas (2006), who did not identify evaporation from the alluvium as a sensitive factor.

Total lateral seepage into the weathered basement riverbanks across the whole short dry season ranged from 1,700 – 5,400 m³ between sites. It accounts for a maximum of 97% of total loss. Despite limited water level measurements and potential recall and overly positive biases in the interview data, higher flow rates, concurrent with greater empirical evidence suggest that lateral seepage is a larger contributor to loss than longitudinal seepage. Lateral seepage in the current study was found to be sensitive to specific yield of the alluvium, the values of which were derived from literature. Whilst modelled to vary between each reach, specific yield will likely vary across the river channel more so than was modelled, depending on the composition of the alluvium.

Total longitudinal seepage under the dam wall across the whole short dry season ranged from 0 to 320 m³ between sites, with an average of 1.1 m³/day. It accounts

for a maximum of 12% of total loss. Flow rates, pooling, and observations of dam wall construction suggest that there is some longitudinal seepage at five of the studied sites. However, low simulated flow rates and less empirical evidence of longitudinal seepage compared to lateral suggest that this is not a loss pathway of substantial concern.

6.5.2 Water availability

Estimated groundwater volume from mature sites at the start of the short dry season, with the assumption made of fully saturated alluvium, ranged from 1,300 – 4,200 m³, with an average of 2,700 m³. At the end of the season, the volume ranged from 390 – 2,400 m³, with an average of 1,200 m³. These former estimates are within a similar range to those at the start of the dry season in literature. Eisma & Merwade (2020), using a specific yield of 0.4 estimated the water volume of three sand dams to range from 1,310 - 2,880 m³, whilst Neufeld et al. (2021) estimated median values of between 144.2 and 302.8 m³. Hut et al. (2008), using a specific yield of 0.3, estimated the maximum water volume of one site as 2,800 m³, whilst Ndekezi et al. (2023), using specific yields of between 0.2 and 0.3 estimated the maximum water volumes from three sites to range from 90.0 to 1,710.6 m³. They found that one dam became dry in June due to thin sediment build up. Variability in water volumes between sites in the current study and literature indicate that sand dams have different water supply capacities depending on site, climatic, and hydrogeological parameters, and human activity.

Integrating the maximum volume of abstraction across the dry seasons into each model shows that each site was able to meet these abstraction demands. Conversely, Ndekezi et al. (2023) found that total water storage after accounting for loss was unable to meet estimated daily water demand of between 6.9 and 16.0 m³ at their three studied sites. Whilst Hut et al. (2008) found that demand was being met, estimated values of demand were much smaller. Using a subsurface model, they concluded that a small dam in Kitui was able to meet domestic water demands (15 L/person/day or 1 m³/day) of all users (n=70). Clearly there is contention in literature as to the capacity of sand dam storage to meet water demands, which derive from substantial variations in estimates of

both. By deriving abstraction values from telemetered handpump data, the current study uses a more accurate estimation of abstraction compared to other methods, which are usually based on population numbers, recall, and minimum recommended water requirements.

Greater loss would be expected in the long dry season, leading to a smaller water volume as shown by Ndekezi et al. (2023). Abstraction data from Ritchie et al. (2023) indicates a higher median and maximum abstraction of 47.6 m³ and 743.2 m³ respectively across this period. Running the models across the long dry season indicates that there is still water left in the alluvium of each site when accounting for these higher rates of abstraction. This is due to inflow of water from the riverbanks. The results therefore indicate that even when accounting for maximum likely abstraction: a.) abstraction accounts for only a small volume of water loss from the sites (up to 16% of total water stored), b.) the sites are able to meet the average sand dam handpump needs, and c.) abstraction from handpumps at these sites could be increased, if necessary.

6.6 Conclusion

This study, using analytical modelling validated by empirical data and literature, highlights the contribution that each loss pathway has on water availability in sand dams. Lateral seepage has the greatest influence on total loss, whilst longitudinal loss and abstraction are generally the lowest contributors. Such insights indicate where efforts can be focussed in order to maximise potential benefits from sand dams, such as agriculture on the riverbanks. Compatibility between the empirical and modelled results increases confidence in the model and highlights that simple field observations can help to suggest sites where seepage may be relatively more of a concern and where remediation may be needed.

Seepage has been shown to be most sensitive to riverbed and dam wall width, ΔH , specific yield and length of alluvium, and hydraulic conductivity and thickness of saprock under the dam wall. Knowledge of such sensitivity is useful for improving site selection and construction criteria in order to design sand dams that better meet their intended purpose, especially highlighting the importance of construction on unweathered bedrock.

The study adds to the sparse but growing knowledge on the interaction between sand dams and the surrounding weathered basement. The relatively high rates of lateral seepage occurring at sand dams highlights that they have some recharge potential to the surrounding aquifer, positively impacting the local water table and vegetation growth. However, at each site, there is water available in the alluvium at the end of the dry seasons, with storage being sufficient to meet abstraction needs of sand dam users. This highlights that these sand dams are able to provide for current abstraction behaviour and to contribute valuably to water security in drylands.

6.7 References

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7 Discussion

7.1 Introduction

This thesis addresses and achieves its aim: “To evaluate spatial and temporal water losses from sand dams in order to understand their storage potential and their contribution to water availability within the river channel and surrounding weathered basement aquifer.” The thesis combines several methods: analysis of telemetered abstraction data, geophysical surveys, analytical modelling, and collection of empirical data. It was the first study to undertake modelling focussed on quantifying different types of seepage losses and to use 2D geophysics at sand dam sites. The thesis demonstrates that whilst each sand dam is unique, they all lose water to varying degrees via seepage, abstraction, and evaporation, contributing to water availability for human use and in the surrounding aquifer.

This final chapter synthesises and evaluates the findings from this thesis in order to highlight how and where each objective and overall aim has been met. The implications of results and contribution to knowledge, uncertainties and further work suggestions are discussed.

7.2 Local recharge function of sand dams

Modelled flows rates, low resistivity signatures downstream and at shallow depths beneath the weathered basement surface, relatively low abstraction rates across the dry seasons compared to estimated stored water volumes at the start of the dry season, and empirical evidence suggest seepage and subsequent recharge to the surrounding environment exists at all sites.

Seepage, whilst a loss for water storage upstream, can be beneficial for other uses, with pooling downstream being used for livestock, laundry, and bathing (Parker et al., 2022). Similarly, recharge of the water tables in the weathered basement can enhance agricultural activity and potentially increase abstractable water further from the riverbeds (Borst & Haas, 2006; Eisma & Merwade, 2020; Villani et al., 2018).

7.2.1 Lateral seepage

Whilst several studies have measured, modelled, remotely sensed, or assumed lateral seepage, only Borst & Haas (2006), Ndekezi et al. (2023), Quinn et al. (2019) and Yifru et al. (2020) provide quantified values. Average daily lateral flow rates in this thesis range from 23 - 73 m³ between sites (average of 31 m³). These are higher than Borst & Haas (2006) (5.6 m³), Ndekezi et al. (2023) (max 4.0 m³), and Quinn et al. (2019) (max 12.3 m³), who used water balances. Values in this thesis are more similar to Yifru et al. (2020) (34.2 m³), who used MODFLOW to simulate the influence of the riverbed water level on groundwater level in the surrounding aquifer. The higher average flow rates calculated in this thesis are in part due to much higher rates at the start of the dry season when the alluvium was modelled to be fully saturated. This was not the case in Quinn et al. (2019) or Borst & Haas (2006) but was in Ndekezi et al. (2023). Further, the lateral seepage values in this thesis include evapotranspiration, which has been shown to account for a high proportion of lateral seepage at some sites. Finally, values are derived from calculations rather than from the residual of other loss pathways, which may help to further explain some of the difference.

Eisma & Merwade (2020) estimated that the seepage rate under the dam wall and into the weathered basement remained essentially constant. The simulated results in this thesis found rates to decrease over time as the hydraulic gradient decreases. The purpose of their study, however, was not to quantify seepage and a larger focus was given to exploring evaporation as a loss mechanism. Hut et al. (2008) assumed seepage into the weathered basement to be slow, suggesting that it may take many flash floods or seasons before the water levels in the surrounding aquifer are at equilibrium with those in the riverbed. Conversely, the findings from this thesis found lateral seepage rates to be relatively high. The model indicates that losses can cause the water level in the riverbed to fall below that in the weathered basement. The hydraulic gradient reverses and water subsequently seeps back into the riverbed. This meant that the modelled riverbed alluvium did not run dry, even by the end of the dry season. Such a pattern was also observed by Hut et al. (2008), who found, from modelling, a “saw-tooth” pattern of infiltration into and out of the riverbed during pumping.

Empirical evidence of lateral seepage is somewhat supported by geophysical inversions and previous studies. The proportion of unweathered rock along the base of the riverbank was observed as a proxy for the nature of the subsurface beneath the riverbank. Geophysical inversions support these surface observations. Sites with more observed unweathered bedrock along the surface (hypothesised to lose less water), also generally had higher resistivity signatures along these boundaries. Increased health and density of vegetation in this thesis is supported by Demessie & Woldeyohannes (2024), Eisma & Merwade (2020, 2021), Manzi & Kuria (2011), and Ryan & Elsner (2016). They calculated higher NDVI, evapotranspiration, and biomass production at sand dams compared to control sites. This suggests the holistic benefits that sand dams can have on local ecology and potentially on local water availability, although the increase in vegetation will result in a higher rate of loss to evapotranspiration. Demessie & Woldeyohannes (2024) used Water Productivity through Open access of Remotely sensed derived data (WaPOR) and found that evapotranspiration and biomass production increased along plots adjacent to sand dams post- compared to pre-construction. Eisma & Merwade (2020) similarly found that the two functioning sand dams in their study individually supported more vegetation than the non-functioning dam. This increase in vegetation is, however, contested by Neufeld et al. (2021), who found no significant difference in NDVI attributed to greening at sand dam compared to control sites. Despite vegetative growth being supported at some sites, the extent was limited, with the difference potentially because they studied a larger number of dams across a normal dry season whilst some other studies specifically studied periods of drought. The results from Eisma and Merwade (2020) suggest that topography is also impactful on vegetation. They found that areas with flat land or gentle slopes, at lower elevations above the riverbed had greater vegetation cover. This may therefore further help to explain differences between studies. These differences highlight the need for future studies to help confirm or deny the benefits that seepage from sand dams may be having on average vegetation health and density, and not just during periods of drought.

Results from modelling, geophysical inversions, and empirical evidence suggest at which sites lateral seepage is highest. The findings from each method, however, sometimes vary. In general, there is more correlation between the geophysics and modelling results. Limited empirical indicators of seepage and a limited number of observations, based only on three mature and three new sites, constrains the accuracy of the empirical data. Whilst it provides some insight and is a useful first step in truthing modelled results, limitations in its application are recognised. Limitations in the geophysical inversions are also recognised in uncertainties related to lateral seepage. Low resistivity signatures in the riverbanks cannot solely be attributed to saturation, with clay content also having an impact. Furthermore, resistivity values cited for saturated saprolite extend up to 700 $\Omega\cdot\text{m}$ (Elster et al., 2014). This means that sites without very low resistivity signatures in the surrounding saprolite can still be saturated. Further, the site with the highest resistivity signatures and most outcropping unweathered rock along the base of the riverbank has the highest rates of lateral seepage. This may be because the surface and shallow subsurface expressions of rock are not vertically continuous, potentially impeding shallow but not deeper lateral seepage. It may also be attributed to the unweathered rock not being continuous along the base of the riverbank. In spite of this, lower resistivity values are generally found in the surrounding weathered basement of the upstream compared to downstream profiles. This difference highlights the impact of lateral seepage from the upstream trapped alluvium at all sites. Finally, whilst the equation used in the analytical model was deemed the best option for simulating lateral seepage, uncertainties in modelling will always exist. In this thesis these largely derive from limited calibration points and minimal water level elevations in the weathered basement. Despite some disparity in lateral seepage results between the three methodologies, the generally stronger correlation between the geophysical inversions and modelling provides confidence in the findings. These two approaches were the more robust and comprehensive methods, underscoring the validity of the results.

7.2.2 Sub-vertical seepage

Trincheria et al. (2015) reports that if the foundation of a sand dam is laid on permeable material, the accumulated water in the trapped alluvium may infiltrate to lower layers of sediment. Woodhouse (1991) further states that tectonic movements can create faulting which can cause impermeable rocks to leak. Despite this knowledge, no previous studies have assessed the nature of the subsurface beneath the trapped alluvium to beyond 1 m (Borst & Haas, 2006). Findings of weathered rock beneath the trapped alluvium disprove previous assumptions of unweathered rock underlying the alluvial aquifers (Ertsen et al., 2005; Hoogmoed et al., 2007; Nissen-Petersen, 1997; Quilis et al., 2009). This finding valuably adds to knowledge of how sand dams interact with their surroundings, indicating the presence of sub-vertical seepage.

The geophysics profiles suggest sites with deeper unweathered bedrock are likely to be more impacted by this sub-vertical flow component, compared to those shallowly underlain by unweathered bedrock, which will impede flow. The site with the shallowest unweathered bedrock, for example, lost amongst the least water to seepage. The mature site with the highest seepage rate was characterised by the deepest water levels and highest shallow resistivity signatures of all the mature sites. This may be explained by faster seepage rates into the surrounding aquifer as a result of higher transmissivity, reducing the water content. The site with the second shallowest bedrock, however, was simulated to have the highest level of water loss due to seepage. High seepage rates were due to a large plan area. This suggests that even at sites where unweathered bedrock is relatively shallow, substantial lateral losses can still occur due to the nature of the shallow subsurface. Despite this, it remains beneficial to target sites with relatively shallow unweathered bedrock beneath the riverbed and surrounding area. In doing so, even if lateral losses occur, this water can still have positive benefits on water availability within the surrounding shallow weathered basement aquifer.

7.2.3 Longitudinal seepage

By quantifying longitudinal seepage for the first time, this thesis supports previous studies which have assumed or suggested sand dam walls to be constructed onto slightly weathered rock (Eisma & Merwade, 2021; Gezahegne, 1986; Gijsbertsen, 2007; Hut et al., 2008; Maddrell, 2018; Quinn et al., 2019). Average daily longitudinal seepage ranged from 0 - 4.3 m³ between sites (average of 1.1 m³). It was consequentially found to be a loss pathway of low concern. The geophysical inversions support that the dam walls are largely performing their function of holding back water. Whilst there are some low resistivity signatures downstream of the dam walls, there is generally a much greater volume of low resistivity material upstream, indicating minimal seepage. There is similarly less empirical evidence of longitudinal compared to lateral seepage.

Empirical evidence of longitudinal seepage in the form of pooling and construction onto slightly weathered bedrock is supported by previous studies, geophysical inversions, and simulated flow rates. Pooling was found to be the deepest and most extensive at the same site at which longitudinal seepage was highest and resistivity values on the downstream side of the dam wall were lowest. Pooling or running water downstream was also observed by Jansen (2007), Parker et al. (2022), Neufeld et al. (2021), and Trinchiera et al. (2015), at 19, 66, 30, and 37% of sites respectively. They assumed this to be as a result of longitudinal seepage under or around the dam wall. The observation of dam wall construction onto slightly weathered bedrock is similarly supported by Borst & Haas (2006) who report that construction sometimes occurs without an impervious foundation when time for completion is running out. They state that water may subsequently flow slowly through the weathered and fractured rock, seeping back into the riverbed downstream. The geophysical inversions support field observations of the majority of studied dam walls being constructed onto slightly weathered bedrock.

7.2.4 Relative importance of seepage

The above evidence indicates that sand dams do interact with their surrounding basement aquifers, providing a partial recharge function. This supports

Hoogmoed et al. (2007) and Yifru et al. (2018) who conclude that the groundwater level around the sand dam area increases. Further, it supports the assumptions of Hut et al. (2008) and Quilis et al. (2009), that water flows between the modelled sand dams and their surrounding aquifers. This thesis found seepage to be a larger contributor to total loss (up to 98%) than evaporation from bare alluvium and abstraction, which contributed a maximum of 12 and 1% respectively to total loss across the short dry season. Previous studies have found evapotranspiration to be the largest contributor to loss (Borst & Haas., 2006; Eisma & Merwade., 2020; Ndekezi et al., 2023). This is due to the inclusion of evapotranspiration losses from vegetation in the riverbank, as well as evaporation from the riverbed. Evaporation from riverbeds has been found to be negligible once infiltration has occurred (Andersen et al., 1998; Borst & Haas, 2006). Whilst it is acknowledged that evapotranspiration can account for a large part of water losses from rivers in arid areas, the volume depends on the amount of vegetation, depth of water table, and local climate (Jansen, 2007). Evapotranspiration from the riverbanks was not included as a separate loss pathway in this thesis but was accounted for as a component of the water that is being lost laterally into the weathered basement. Estimates of the volume of water lost to evapotranspiration show, similarly to Borst & Haas. (2006), Eisma & Merwade. (2020), and Ndekezi et al. (2023), the relatively large contribution that evapotranspiration can make to loss, (contributing to between 6 and 85% of total loss at individual sites). The findings from this thesis have highlighted the often underestimated impact that seepage into the weathered basement has on overall losses from sand dams. If the majority of this water, however, is lost to evapotranspiration, which is the case at four of the studied sites, then the possible benefit of such seepage in the surrounding aquifer for abstraction may be minimal.

The overall magnitude and consequent impact of lateral seepage on the surrounding aquifer is likely moderate, in part due to loss to evapotranspiration, in the large scale context of water availability. Eisma and Merwade (2021) used a generalised linear model developed using Gravity Recovery and Climate Experiment (GRACE) satellite data to assess the large scale impact of sand dams on water storage across the three main sand dam counties in Kenya. Eisma and

Merwade (2021) found that in April and November (which they found to be the highest rainfall months), sand dams had a positive impact on regional water storage. For the rest of the year, they found no discernible significant impact of sand dams on regional water storage at a scale which GRACE could detect (several hundred km). This indicates that whilst sand dams do store water, they generally have limited impact on water availability in their watersheds. Using NDVI, Eisma & Merwade (2021) did, however, find a significant impact of sand dams on vegetation, indicating the small-scale impact of sand dams on water storage (in line with the aforementioned remote sensing studies). This is supported by Ertsen et al. (2005), Hoogmoed et al. (2007), Hut et al. (2008), Quilis et al. (2009), Ryan & Elsner (2016), and Strohschein (2016), who have found sand dams to impact areas up to 100 m from the riverbed, extending up to 350 m upstream. Based on the area of Makueni (8,035 km²) and an average annual rainfall here of 775 mm, annual precipitation volume across Makueni is approximately 6,227,000,000 m³. According to Hoogmoed et al. (2007), approximately 0.74% of precipitation recharges groundwater (as a result of evaporation and soil properties). There are approximately 340 sand dams in Makueni (Eisma et al., 2024, in press) and this thesis calculated an average lateral seepage rate from one site across the short dry season of 2,900.0 m³. This would result in a total seepage rate of approximately 996,000 m³ across Makueni (from 340 sand dams), which is only 2.2% of annual recharge from precipitation. This supports the conclusion that whilst sand dams do lose water to seepage, the wider impact on water storage in the surrounding aquifer is minimal.

7.3 Are sand dams providing sufficient storage for abstraction needs?

Estimated groundwater volume in sand dams has been found to vary substantially, with a disparity in storage potential identified by previous studies (Trincheria et al., 2018; Eisma & Merwade, 2020; Quinn et al., 2019). Water storage from seven studies ranged from 144 - 30,851 m³, with a median of 2,483 m³ (Eisma & Merwade., 2020; Hut et al., 2008; Lasage et al., 2015; Ndekezi et al., 2023; Neufeld et al., 2021; Quinn et al., 2019; Simon, 2019). This is very

similar to the average from the mature sites in this thesis of 2,700 m³, calculated from a range of 1,300 - 4,200 m³. The geophysical inversions similarly suggest a disparity in volume of saturated trapped alluvium. The site at which low resistivity material extends furthest upstream corresponds to the site with the largest estimated groundwater volume. The site with the smallest estimated groundwater volume has the deepest expression of low resistivity material. This may be due to greater volumes of water loss into the underlying weathered basement here, giving low resistivity signatures below the trapped alluvium and smaller groundwater volumes in the trapped alluvium. It may also be due to higher levels of clay in the underlying weathered basemen here.

Previous research has found conflicting evidence with regards to sand dams being able to provide sufficient water to meet demand (Borst & Haas, 2006; Hanson & Nilsson, 1986; Jansen, 2007; Ndekezi et al., 2023; Neufeld et al., 2021; Ngugi et al., 2020; Quilis et al., 2009; Simon, 2019; Trincheria et al., 2015). Similarly, the results from this thesis are mixed. The telemetered abstraction data suggests that not all sites are able to meet demand, whilst the modelled results suggest the opposite.

Water level measurements mid-way through the short and long dry seasons from this thesis and Quinn et al. (2019) confirm the presence of water at this point in time. The telemetered handpump data shows that by the end of the long dry season, at least 81% of sites (n=21) still had some water within the trapped alluvium. Findings from Borst & Haas (2006), Eisma & Merwade (2020), Hoogmoed et al. (2007), and Ndekezi et al. (2023) also provide insight into water presence at the end of the dry season. By the end of the long dry season, Borst & Haas (2006) recorded minimal water in two divers in the trapped alluvium approximately 30 and 70 m upstream on 07.11.2005 (day before rainfall). Water was measured as 1.63 and 1.77 m bgl, approximately only 0.05 m above the weathered basement. Eisma & Merwade (2020) used water table monitoring wells at three sites. At one site, water was only detected in the well closest to the sand dam up to two days following a rainfall event due to a 1.2 m thick silt layer beginning at a depth of 0.5 m bgl. Another site had “very little abstractable water”

ten weeks after the last rainfall event, whilst the third site retained abstractable water for fifteen weeks after the last rainfall. These findings show that two thirds of the studied sites couldn't meet dry season water needs. Ndekezi et al. (2023) found that one dam became dry in June due to thin sediment build up. Their other two studied sites retained water for up to three months but were dry by the end of September. Hoogmoed et al. (2007) on the other hand, installed piezometers around one sand dam and recorded water in the trapped alluvium throughout the dry seasons. They concluded, from modelling, that the minimum storage (by the end of the long dry season) was 1,660 m³. This supports the findings of this thesis that water may still be available within the trapped alluvium of some sand dams by the end of the dry seasons.

Analysis of the telemetered abstraction data shows that abstraction is highly variable over time and between the 26 studied sites. Such heterogeneity in handpump use was also found by Thomson et al. (2019). Median daily abstraction in this thesis across the 31-months across all sites was 0.1 m³/day. Thomson et al. (2019), using the same smart handpump technology as this thesis, calculated a higher average abstraction of 1.5 m³/day across 266 groundwater handpumps in Kenya. They used mean, rather than median abstraction, which is likely, in part, the cause of the higher calculated abstraction volumes. Furthermore, as they studied abstraction from Afridev handpumps not at sand dams, the disparity highlights the difference in use of sand dam compared to regular handpumps. This is likely attributed to a combination of differences in water availability, water use preferences and norms. It is also likely related to the additional use of other abstraction methods at sand dams including scoop holes and pooled water, the former of which was estimated by Quinn et al., (2019) to be up to six times higher than the median handpump abstraction from the telemetered data.

Whilst the telemetered abstraction data shows that water was often still being abstracted by the end of the long dry season, abstraction was heterogenous. Although abstraction was modest (median of 0.2 m³/day), 59% of sites (n=13), were still meeting the bare minimum drinking water needs of all users. The number of users at each site, especially in communities with pastoral migration,

may change over time, providing some uncertainty in the number of people served. The absolute abstraction figures, nonetheless, remain modest.

Conversely, the simulated water volumes from the six modelled sites suggest that sand dams are able to meet abstraction needs (at least 6.1 m³/day). 100% of the sites comfortably met needs throughout the dry seasons, highlighting the contribution they are able to make to water security. Jansen (2007) similarly found that a water use of 20 m³/day could be sustained from a modelled sand dam for 120 days. Using field data and literature, they built a surface flow model, which are rare in the study of sand dams, as they store water below the surface, but can provide insight into optimum sand dam design.

In most reaches at each site in this thesis, the water level in the riverbank lay above the base of the alluvium. Under such conditions, water will flow back into the alluvium to recharge what has been lost once the water level in the alluvium has dropped below that in the weathered basement. This is supported by Quinn et al. (2019), who found that one site gained water throughout the whole of the long dry season. Once equilibrium is reached, the water levels in the riverbank will likely begin to fall. In cases where the water level in the riverbank falls below the base of the alluvium, however, water will not flow back into the riverbed to recharge the alluvium, and sites will not necessarily be able to meet abstraction needs. In this thesis, the water level in the riverbank was modelled to remain constant. It is recognised that in reality, this will unlikely be the case. This constraint was used however, as it was unknown how far into the weathered basement the rise in water table would impact, making rate of water table rise uncertain. This was especially due to the unknown impact of the water table further into the weather basement outside the impact of a sand dam. It is possible, that with a changing water table in the riverbank that seepage and subsequent stored water volumes may vary and may be unable to meet abstraction needs so easily. Having said this, findings from previous studies of inflows from the riverbanks, as well as measured water level elevations in this thesis, which show good calibration with the modelled water levels help to improve confidence in the water storage capacities of these sites. Furthermore, any potential overestimation

in seepage is somewhat balanced by water level measurements in the weathered basement having been taken mid-way through the dry season. If the water table rises as a result of seepage, it can be assumed that the water table was lower at the start of the dry season, which would have resulted in higher seepage rates at this point.

Water availability in the alluvium at the end of the dry seasons, coupled with abstraction capabilities, and unweathered bedrock at certain locations, all indicate that sand dams provide notable storage functions. Despite >100% of initial groundwater volume being lost over the short dry season at some of the modelled sites, inflow from the weathered basement and upstream of the trapped alluvium mean they can serve as effective storage facilities. Water demands are able to be met, with a maximum reduction in storage across the short dry season of 85% (lost to seepage, evaporation, and abstraction).

7.4 Are sand dams being used to their full potential?

There is evidently a disconnect between the telemetered abstraction data, which suggests that not all sites are able to meet abstraction needs, and the modelled results, which suggest the opposite. The modelled results suggest that at least 6.1 m³/day (the maximum abstracted from the most highly used smart handpump) can be supported by all of the modelled sand dams through the long dry season. This compares to an average of 0.4 m³/day being abstracted through the long dry season from the 26 studied smart handpumps.

There are many possible explanations for the heterogeneity in abstraction observed between the 26 sites with telemetered abstraction data, linked to both water availability and human behaviour. However, it is crucial to recognise that the abstraction data serves only as a proxy for water availability. In other words, low abstraction may not necessarily indicate low availability and may instead be attributed to human preference and behaviour (Chan, 2019; Devoto et al., 2012; Elliott et al., 2017; Howard, 2002; Jiang & Rohendi, 2018; Neufeld et al., 2021; Parameswari et al., 2016; WHO & UNICEF, 2017). It is especially likely that this may be the case at the twenty sites which showed distinct increases or relative stability in abstraction across at least some long dry seasons.

Neufeld et al. (2021), for example, took sediment cores from 97 sand dams across Kenya. Sediment samples were air dried, ground, and sorted by size. The percentage of cores containing water was used as an estimate of water presence at each dam on the date of sampling. They found no significant difference between sites with water in core samples and sites with active water abstraction. Neither did they find a correlation between sites with water in core samples and self-reported water use. The average core depth, however, was only 0.7 m, meaning that alluvium with deeper water tables would not be included in the analysis, despite water at this depth being available for abstraction. Simon (2019), found from interviews in Somaliland, that at only two of five communities did respondents claim sand dams to be their preferred water source for domestic use in the rainy and dry seasons. They additionally found this to be the case at one site in just the dry season. At the other two sites, other sources, including community boreholes, household rainwater harvesting, or vended water were the preferred options for domestic use in both the rainy and dry seasons. Reasons for sand dams not being the preferred water source included convenience, queuing times, and dam wall collapse. For other uses such as livestock and irrigation, people in all five communities claimed to use sand dam water via wells in the immediate riverbanks or scoop holes in the rainy and dry seasons, among other sources. This again shows the high use of sand dams for agriculture compared to other uses. People generally reported water to be available throughout the dry seasons since dam construction, although in low volumes by the end of the season. The above results suggest that water presence may not be the primary determinant of variations in water use between sites, with social factors potentially being more important than physical factors in determining water abstraction from sand dams. The disconnect between the telemetered and modelled results strongly suggests that this is the case – that people may not be making full use of the water stored in sand dams for one of multiple social reasons.

At the sixteen sites at which there was a decline telemetered abstraction data across at least one of the analysed long dry seasons it is likely that a decline in

water availability had at least some control on the patterns of abstraction. Such a pattern was observed by (Macdonald et al., 2019), who found that water levels in hand dug wells in Ethiopia declined rapidly in the dry season. The alluvial aquifers of sand dams are more comparable to such abstraction points, rather than the boreholes in the study by Macdonald et al. (2019), which extended between 40 and 100 m deep and in which no significant decline in yield was observed through the dry season. Such a response was not, however, observed by Thomson et al. (2019), who recorded sustained average abstraction across 266 studied handpumps in Kenya. These were fitted to either hand dug wells or boreholes, yet no distinction in abstraction pattern is made between the two.

A regression model on the telemetered abstraction data revealed that levels of abstraction were significantly higher when actual salinity, livestock use, and dam wall area were greater. These results use interview data collected by Chan (2019), who undertook basic analysis of the interview and telemetered abstraction data over a two-month period. Most of the findings were consistent with those of Chan (2019), considering the same interview data was analysed. Chan (2019) however, contrary to this thesis, found that abstraction from sites perceived as saline was similar to those reported as non-saline. This difference may be attributed to the limited time frame of the data analysis by Chan (2019) (May - June 2019). Reduction in salinity due to rainfall in May (Kitheka, 2016), may have altered people's abstraction habits of water generally perceived as saline. Furthermore, Chan (2019) undertook descriptive statistics on each individual parameter, whilst this thesis undertook a regression analysis in order to account for all of the parameters at the same time.

The findings from the regression model support the simulated results from the six modelled sites by indicating that factors other than water availability in the sand dams are likely impacting abstraction. Despite variability and some uncertainty in the water storage capabilities and use of sand dams, previous studies, model calibration, and empirical evidence help to improve trust in the telemetered and modelled results. The evidence supports the conclusion that the studied sand dams are able to provide for the abstraction needs of users, with people likely not

making full use of stored water, with social factors having a strong control on water use, despite availability.

7.5 Sand dam success rate

Comparing abstraction potential from a normal dryland sand river with a river augmented with a sand dam reveals differences in water availability. Lower resistivity signatures in the trapped alluvium post- compared to pre-construction suggest likely increases in water content. Additionally, calculations of water storage capacity and measured water level elevations further support the conclusion that access to water is enhanced post-construction. Groundwater availability at studied sites was found to increase by between 34 - 360% from pre- to post-construction.

By studying three new sites, this thesis provides a novel insight into the functionality of sand dams without the bias that exists in selecting mature sites for research studies. The three sites had partially filled with alluvium one year since construction. As well as this, a slight decrease in resistivity in and directly below the trapped alluvium suggest an increase in water content. Groundwater stored at two of the sites was estimated to be $<500 \text{ m}^3$ at the start of the short dry season, approximately 2.5 - 8 times smaller than at the mature sites. This is due to a thinner accumulation of alluvium build up. At the dam walls of the three new sites, alluvium build-up was 18, 28, and 88% of the height of the dam walls. This highlights that substantially more alluvium build up is needed at the former two sites before full capacity is reached. Based on these estimates, such filling could take more than five years.

The third new site had a comparable groundwater volume at the start of the short dry season to the mature sites and a greater volume than all sites at the end of the short dry season. This was due to the majority of water loss being from surface water. Despite having a thinner accumulation of saturated alluvium than the mature sites, the riverbed width here was the greatest of any of the dams. This somewhat supports literature which claims sand dams on wide rivers can typically fill within one season (Maddrell & Neal, 2012). This site was hypothesised to be successful from the outset due to fast sediment accumulation

due to the width and coarse sediment load (J. Nyangoka, personal communications, February 2022). Sediment analysis at this site found generally coarse, slightly gravelly sand. At the other two sites, the composition was more variable, with more clay and fine - medium sand. The findings one year post-construction support the hypothesis of fast sediment accumulation at this site. These findings, whilst limited to one site, suggest that relatively successful sites may be able to be identified by studying the alluvium in the existing riverbed. They support construction on rivers with high coarse sediment load (Maddrell, 2018) and highlight the importance of local knowledge.

Each of the new sites were already being utilised one year post-construction. Despite not being completely filled with alluvium, surface water at each site extended to different distances upstream and added to the overall availability of water. Whilst no handpump abstraction was occurring at any of the new sites, surface water both up- and down-stream was being utilised through pumping and collection via jerry cans. Water use was predominantly in the form of irrigated agriculture on the sides of the riverbeds.

According to results from Eisma & Merwade (2020), Nissen-Petersen (2010), Pauw et al. (2008), Trincheria et al. (2015, 2018), and Viducich (2015), approximately 50% of sand dams in Kenya are non-functioning. Failure is cited to largely be as a result of siltation due to one-stage construction, evaporation, construction on weathered bedrock, rivers bypassing the walls, poor protection of banks, filling with little water, washing away, and pollution (Nissen-Petersen, 2010; Pauw et al., 2008; Trincheria et al., 2015; Yifru et al., 2021). No studies on failure report the age of the dams. If construction, site selection, and maintenance can be improved as to minimise such contributors to failure, then the functionality rate of sites should be improved. Results from this thesis go some way to understanding how seepage (one failure mechanism) can be reduced.

Clearly, it is impossible to say whether each of the three new sites will completely fill with alluvium and become successfully functioning sand dams over the long-term. However, results one year post-construction indicate that each are on their way to filling, but at quite different rates. Whilst none of the rivers are bypassing

the dam walls, each had accumulations of silt. Evidently, the faster that each site fills with alluvium, the faster that the benefits of sand dams can be felt, including relative protection from evaporation and mosquitoes (Eisma & Merwade, 2020; Pauw et al., 2008; Quinn et al., 2018). Whilst the use of each dam within the first year indicates short-term storage success, only time will reveal the sustainability of these three new sites.

7.6 The relative contribution of sand dams to dryland water security

Without the construction of a sand dam, run-off in the rainy season would be lost largely to evaporation and to downstream flow. Hence, their construction (as long as successful), increases absolute water availability. Whilst this research has demonstrated that the alluvium of sand dams is generally able to retain at least some water by the end of the dry season, questions remain as to a.) whether this volume of water provided is sufficient relative to their cost and b.) if and how sand dams are making or can make a meaningful impact on water security in drylands in the future.

According to Maddrell and Neal (2013), sand dams are primarily designed to provide water for domestic purposes and irrigation. In spite of this, Parker et al. (2020) found their three studied dams were being used for multiple additional purposes from brick making to laundry. They found, however, that handpumps were only being used for domestic purposes including drinking, cooking, hygiene, and cleaning. The results on handpump abstraction in chapter 4 highlight that whilst a maximum daily handpump abstraction of 20.5 m³ was recorded from one site, median daily handpump abstraction was only 0.1 m³. Considering this generally low volume abstracted from handpumps, it is questionable as to whether sand dams are economically viable in terms of an improved water supply for domestic use. This is especially the case when considering that up to only 16% of estimated stored water was being abstracted by handpumps based on the telemetered abstraction data.

Whilst total water use from multiple sites has not been fully quantified by any study or organisation to date, estimates from Quinn et al., (2019) suggest that

just from scoop holes, abstraction is likely at least six-times higher than that from handpumps according to the telemetered data in this study. Combine this with the unquantified volume of water being pumped from agricultural wells at some sites and the cost-effectiveness of sand dams may be substantially improved. Whilst Parker et al. (2020) found that scoop holes (where present) were predominantly used for similar domestic purposes to handpumps, pooled water downstream and open agricultural wells were used predominantly for irrigation and livestock. Further work is necessary in order to understand whether the findings from Parker et al. (2020) in relation to scoop hole use are relatively universal. If people are using scoop holes rather than handpumps for the same purposes', questions remain as to why, and whether work can be done to increase the use of the available improved source.

When one considers that scoop holes are an unimproved source and should not, ideally, be promoted for direct human use, it seems reasonable to suggest that sand dams have greater benefits for agricultural and livestock needs, rather than for direct use by humans. Further research, however, is needed to understand the relative volumes of water being used for each purpose, in order to confirm this benefit in terms of volume, rather than just quality.

7.7 Implications for dryland water security

The research findings discussed in this thesis have multiple implications for dryland water security, being especially beneficial for sand dam practitioners including NGOs, local, and national governments. The research has positive implications for site selection, dam construction, water use practices, funding applications, and dryland water management decisions.

7.7.1 Site selection and dam construction

Improved knowledge of which variables may impact abstraction and seepage is useful for decision makers when choosing the most appropriate water management technique for a certain situation, providing a more balanced and scientifically rigorous opinion of whether a sand dam is the best option. Knowledge of what impacts seepage has wider relevance for other dryland water

management techniques, such as rock detention structures, subsurface dams, and weirs. The results can be used to inform construction and siting of such structures.

The regression model and sensitivity analysis indicate the significance of abstraction to dam wall area and the sensitivity of seepage to various site and hydrogeological parameters. This provides practical recommendations for site selection and dam construction, suggesting how a site will behave on a spectrum of storage and recharge.

Firstly, construction on or very close to unweathered bedrock is important for minimising the thickness of saprock under the dam wall and reducing the potential for longitudinal seepage and failure. Quilis (2009) did not find groundwater levels to be sensitive to saprock thickness. However, they only assumed a saprock thickness of 0.1 m beneath the riverbed in the model and varied parameters by up to 1.5 times in the sensitivity analysis giving a maximum thickness of only 0.15 m. The results indicate the importance of selecting a site where the trapped alluvium will also be shallowly underlain by unweathered bedrock in order to minimise the sub-vertical component of lateral seepage and maximise storage. Having said this, lateral seepage rates may still be high at such sites depending on the hydraulic gradient between the trapped alluvium and weathered basement, hydraulic conductivity of the weathered basement, and dimensions of the trapped alluvium. The studied sites were located in areas of basement rocks, which generally form low - moderate productivity aquifers. If sand dams were sited within volcanic or unconsolidated sediments, recharge to more productive aquifers could be increased. Whilst this would result in reduced storage and is not recommended for sand dams with such a purpose, such sites could augment local water availability to a greater extent.

Secondly, the thesis results support recommendations by Maddrell (2018) of construction on rivers with coarse alluvial sediment of higher specific yields in order to maximise water storage. An increase in lateral seepage was associated with an increase in specific yield. This is corroborated by Quinn et al. (2019). This increase, however, was due to the corresponding smaller decrease in water

storage and larger ΔH resulting in higher flow rates. Results show that, on balance, a larger specific yield is more beneficial for water storage relative to the volume of water lost. This is supported by Hanson & Nilsson (1986), who state that the specific yield of the alluvium is the determining factor in the storage capacity of a sand dam.

Results from the sensitivity analysis conclude that lateral seepage is most sensitive to riverbed width and length of saturated alluvium, whilst longitudinal seepage is most sensitive to dam wall width. An increase in all three resulted in greater seepage due to greater overall storage. A 100% increase in riverbed width and length of saturated alluvium resulted in 63 - 67% of water being lost to lateral seepage compared to 33% under initial model conditions. Construction of a sand dam with a larger dam wall area may contribute to a larger volume of trapped alluvium accumulating, with the significance of this variable to abstraction supporting the correlation between water volume and abstraction potential. The results show that if this increased area is as a result of a wider dam wall, higher seepage rates may be expected. Nissen-Petersen (2006), similarly suggests that sand dams should not be constructed on riverbeds wider than 25 m due to financial costs. The results of this thesis support such limitation of width in order to reduce seepage. Evidently, lowest seepage would occur under narrow riverbed and short alluvium length conditions, which are not conducive to storing water. Limitations to such conditions are a payoff between seepage, cost, alluvium build-up and subsequent water volume which can be stored. Further research would be needed to find the optimum conditions taking all factors into account.

Lower sensitivity to alluvium thickness, supported by Borst & Haas (2006) suggests that slightly increasing the dam wall area by increasing its height may allow greater alluvium accumulation without leading to such high seepage rates as when the width is increased. It is recognised that the dam wall cannot be infinitely high and is restricted by geology and cost. The results simply offer insight into small changes that could be made to reduce seepage risk. Having said this, Viducich (2015) found that higher dam walls are likely to trap a higher proportion of fine particles, resulting in less water storage. To combat this issue,

constructing the dam wall in stages has been recommended (Trincheria et al., 2015; Viducich, 2015). Sites observed 1 year post-construction in this thesis, whilst filled with some sediment (between 0.2 - 1.2 m trapped alluvium at the dam wall) are also filled with a lot of water. In areas where sediment was exposed once water had been lost, silt accumulation was evident. Whilst this thesis did not assess any sites built in stages which could be used as a control, the evidence does indicate fine particle accumulation when sites are not built in stages.

Whilst these recommendations are focussed on reducing seepage, augmenting seepage is also possible where the water table in the riverbank is higher than that in the trapped alluvium. In order to estimate such behaviour pre-construction, water level elevations can be measured in hand dug observation wells or agricultural wells where available in the riverbanks. Siting dams where the water table adjacent the riverbed is particularly high is encouraged. This research found that whilst >100% of stored water was lost from some sites over the short dry season, the maximum reduction in storage was only 85% due to the inflow of water, predominantly from the riverbanks. This highlights the importance of such recharge. Similar water loss proportions were also found by Ndekezi et al. (2023), who reported that between 57 and 83% of stored water was lost to a combination of evaporation and seepage. Values cited by Trincheria et al. (2018) are slightly lower at 48% and even lower (23%) when inflow from the riverbanks is considered. These lower values are likely due to the lower specific yields used.

The thesis has shown that ERT is a feasible technique for understanding the subsurface conditions beneath a sand dam. Being the first time that 2D geophysics was conducted at sand dams, it adds valuable knowledge to how sand dams interact with their surroundings. Able to indicate the relative depth of unweathered bedrock beneath the riverbed, this thesis demonstrates that ERT could be used in site selection, indicating potential sites that will behave more as storage or recharge structures. The ERT profiles also have wider geological relevance by supporting the typical weathered basement profile and adding to the literature on typical resistivity values recorded for each layer in the weathered basement. A typical sand dam costs €6000 - 10,000 (Ertsen & Hut, 2009; Lasage

et al., 2008; Munyao et al., 2004; Trincheria et al., 2018; Tuinhof & Heederik, 2002). Undertaking ERT surveys costs up to approximately €500/day. Whilst this could add up to 8% to the cost of a sand dam, it would be possible to visit >1 potential site/day depending on the geographical spread of sites. A follow up study comparing water availability at the sites shallowly and deeply underlain by unweathered bedrock would be useful in further ascertaining the cost-benefit analysis of undertaking ERT surveys as part of the siting process.

Finally, according to the widely used sand dam construction manual by Maddrell & Neal (2012), critical factors cited for minimising seepage are: 1.) construction of dam walls on bedrock to 1.5 m wider than the width of peak flood in a typical year, 2.) construction onto bedrock, and 3.) sealing fissures in bedrock. There is no mention of the other parameters shown to be influential on seepage in this thesis. It is hoped, therefore, that these findings can be beneficial for strengthening such construction manuals in their recommendations for seepage minimisation.

7.7.2 Current sites

The framework developed in this thesis for scoring seepage indicators and ranking sites provides a short and easy method for assessing evidence of lateral and longitudinal evidence at sand dam sites. Used in conjunction with the model, it can be used to identify locations of seepage concern, in order for potential remediation measures (such as dam wall foundation repairs) or advantages (such as agriculture) to be taken of such seepage. It can easily be supplemented by sand dam practitioners or academics depending on observations or data availability at sand dam and other water management techniques on dryland rivers. Fair correlation between the empirical data and analytical modelling in this thesis supports the use of the framework in this way.

Furthermore, whilst there is variability in the water storage capabilities of sand dams, the thesis indicates that, in general, they are able to provide for the abstraction needs of users. This insight, combined with an improved understanding gained from future studies into the factors influencing water use patterns could be useful for maximising the utilisation of water storage in sand

dams and harnessing their full benefits. Knowledge of when sand dams are not able to meet abstraction needs is important for ensuring that people are provided with alternative water sources, such as vended water during certain periods.

7.7.3 Funding applications

Finally, the findings demonstrate the positive contribution that sand dams can make to dryland water security. The studied sand dams are recharging the surrounding local aquifer to a degree, whilst also providing sufficient storage functions to meet water demands. Such evidence supports the holistic benefits of sand dams, which can bolster support for funding applications aimed at their implementation. It is recognised that some bias and limitations in site selection mean that results are not universally applicable. The thesis is based on only six sites, three of which were constructed only one year prior to the study. Further, they are all located in the same county in Kenya.

Whilst safely managed water for everyone, in-line with SDG 6 (clean water and sanitation for all), should be the priority, many, especially rural communities in drylands are far from this goal (WHO & UNICEF, 2022). Sand dams are relatively inexpensive and can make relatively substantial contributions to water security when functional and cited optimally. Other water management techniques such as RWH tanks and boreholes have generally higher household costs (Parker et al., 2013). The research also highlights that sand dams can provide water when other sources, especially surface bodies, are compromised. Promoting the use of multiple sources should be encouraged, with sand dams providing benefits for especially agricultural use, leaving other sources available to be prioritised for domestic needs.

Previous studies have assessed sand dam cost-efficiency based on both measured water yields in the field and on assumed water yields based on sand dam dimensions. In the majority of the latter studies, 1 m³ of water costs up to €0.7 (Mati, 2005; Gies et al., 2014; Lasage & Verburg, 2015), which is cheaper than the average price of water in rural Kenya (€1.10) (Stern & Stern, 2011). In studies which estimate water yields in the field, lower storage capacity is concluded. Trincheria et al. (2015) found an exceptionally poor cost-efficiency of

€5,635 per 1 m³ due to a failure of 67% of sites to supply water through the dry season. An annual assessment by Trinchera et al. (2018) estimates an annual cost of €30/household. These differences highlight the importance of rigorous field-based studies in assessing the efficacy of sand dams. Clearly, whilst non-functionality rates remain relatively high, the viability of sand dams as a sustainable solution is questionable. However, it is hoped that through combining local expertise and insights from past and ongoing research findings, the non-functionality rate will decrease, and the cost effectiveness of sand dams will improve.

Whilst sand dams exist across the world's drylands, their prevalence outside of Kenya remains considerably lower (Ritchie et al., 2021). This may be due to the unique and favourable physiographic features, which have resulted in the majority of research and subsequent funding being focussed here (Eisma & Merwade, 2021; Maddrell & Neal, 2012). By highlighting their merits, whilst remembering their limitations, this thesis alongside other research in this field has the potential to facilitate diversification of sand dam construction locations, broadening the impact and accessibility of such water management solutions where physically and socially appropriate to do so.

7.8 Further work recommendations

Analysis of the telemetered abstraction data has highlighted which of the 26 sites are used extensively and which are not, highlighting high heterogeneity in abstraction. Only a limited number of parameters, collected in only one season, were investigated with the aim of understanding such differences. This resulted in some variation in abstraction being unaccounted for in the regression models. Visiting these sites periodically to conduct a greater number of more in-depth interviews on water use behaviour and undertake visual inspections would help to identify, more comprehensively, the causes behind such patterns as either behavioural or physical, indicating what, if anything, can be done to increase levels of abstraction where necessary. Whilst one site, which was installed with a smart handpump was also assessed for seepage in the model, installation of smart handpump technology at the five other modelled sites would be highly

beneficial. This would allow direct comparison between water storage/seepage and patterns of abstraction.

Research would benefit from using the empirical framework developed in this thesis for assessing potential seepage at other sites, alongside the model. This would expand knowledge of variations in seepage between sand dams. The number of indicators included in the framework could be expanded to reflect observations and data collected in the field. Using the model at the new sites in a number of years would enable a comparison of seepage between new and mature sites and would increase the robustness of knowledge of seepage from sand dams. There was some uncertainty in the empirical evidence, especially regarding changes in vegetation health and density between pre- and post-construction based on recall and overly positive biases. Based on this, a comprehensive vegetation survey, similar to that undertaken by Eisma & Merwade, (2020) and guided by botanical expertise, both pre- and post-construction would be highly beneficial in order to ground truth findings from remotely sensed studies and from interviews.

In order to improve confidence in subsurface conditions and the interaction between sand dams and the surrounding weathered basement aquifer, further geophysical work could be conducted. Undertaking higher resolution ERT profiles and combining ERT data with other sources such as seismic geophysics or water chemistry data could help to interpret the subsurface conditions more accurately. Further, conducting a similar study at the new sites in several years to assess change would be beneficial. To add to the geophysics and modelling work, an invasive subsurface study is highly recommended. Ideally, this would include drilling a borehole at at least one site in order to undertake a geological assessment of the subsurface conditions and borehole geophysics. This would further improve confidence in the subsurface conditions and enable more accurate constraining of surface geophysics.

It is possible that the model in this thesis over-estimated the volume of water stored in the sand dams by the end of the dry seasons when accounting for abstraction. To improve confidence in the model, it is highly recommended that a

piezometric network in the riverbed and weathered basement be installed. This would provide a fuller understanding of variable storage, as well as water level elevations and hydraulic gradients between the riverbed and weathered basement over time and with a greater spatial extent. More site-specific parameters should also be collected, namely hydraulic conductivity, specific yield, and evaporation, which, in this thesis were obtained from literature. Certain parameters, including specific yield, transmissivity, and permeability could be obtained from geophysics, such as Magnetic Resonance Soundings (MRS).

Finally, the effectiveness of sand dams lies at the heart of the debate concerning their cost efficiency (Eisma & Merwade, 2021; Trinchera et al., 2015, 2018). Due to uncertainty in failure rate and lifetime of a sand dam compared to benefits offered, a life cycle analysis should be undertaken. Such an assessment should include multiple sites and multiple parameters, including financial cost, age, water storage, use, and loss. This would indicate the benefits and challenges of sand dams compared to other dryland water management techniques. It would thus provide a clearer picture to funders when deciding on the most appropriate techniques to invest in.

7.9 Summary

The research findings effectively addressed the aim and objectives of the thesis. An evaluation of seepage, evaporation, and abstraction from sand dams demonstrates their practicality as a dryland water management technique under specific site and hydrogeological conditions. Handpump abstraction indicates water availability in the river channel, whilst evidence of lateral and longitudinal seepage indicates enhancement of local water availability in the surrounding weathered basement aquifer and downstream for use by humans and livestock. Lateral seepage was found to be the greatest overall contributor to loss, followed by evaporation. Such seepage, evident at all modelled sites, highlights the local recharge function of sand dams. Having said this, relatively modest seepage rates when assessed on a regional scale and high evapotranspiration rates suggest that the magnitude and impact of such seepage on large scale water availability is limited.

All modelled sites had water available in the alluvium at the end of the dry seasons, having successfully met the abstraction needs of users. Such water availability demonstrates the water storage capabilities of sand dams, highlighting the positive contribution that they can make to water security in drylands. Low abstraction rates, however, at some sites, alongside some previous findings from literature, suggest either inconsistency in water storage between sites and/or social determinants of water use despite water availability.

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8 Conclusion

Any water sources that are not classed as safely managed should not have to be considered for human use in the 21st Century. Whether that is for an urban population in the UK or a rural population in Kenya. Unfortunately, inequity in global resources, politics, and climatic controls mean that the world is not on track to meet SDG 6. In light of such circumstances, water sources such as sand dams must still be considered as part of the approach to water management in certain areas.

By evaluating losses from sand dams through a combination of seepage, abstraction, and evaporation; this thesis has valuably contributed to the sparse knowledge on the way that sand dams behave in terms of storage and recharge. It highlights the positive impact that they have on local dryland water availability. There are disparities in previous research findings on the storage capabilities of sand dams, whether they can meet abstraction needs, and how they interact with the surrounding environment. This research was necessary to add to the current understanding of their efficacy and sustainability. It fills critical knowledge gaps including the nature of the subsurface beneath sand dams and the quantification of seepage. By providing a balanced view on sand dams which is neither all positive nor all negative, nuances are highlighted in their behaviour. These are important to consider when choosing the most appropriate water management technique.

Depending on their intended purpose (storage or recharge), sand dams can be variably sited. Understanding, from the offset, whether a proposed site is to be predominantly used for abstraction from the alluvium or for recharging the surrounding environment is important. In the majority of cases, if a community requests a sand dam, their aim will be to improve water availability at the sand dam site and its intended purpose will therefore be to maximise storage. This research found that in order to maximise storage, the dam wall must be constructed onto unweathered bedrock. As much as possible of the trapped alluvium should be underlain as shallowly as possible by unweathered bedrock. Such siting can be achieved through the use of non-invasive geophysical

techniques and/or by being more aware of the type and frequency of rock outcrops in the riverbed. This thesis also supports construction on riverbeds composed predominantly of well sorted, coarse sand, which can be realised by a greater awareness of the nature of the alluvium in riverbeds pre-construction. It also encourages a slight increase in dam wall height where possible but supports previous studies in highlighting the merit of completing this construction in stages. Finally, in order to gain water from the surrounding aquifer to augment storage, construction at sites where the water table adjacent the riverbed is particularly shallow is encouraged.

The success of the modelled sites in being able to meet abstraction needs throughout the dry seasons, highlights the storage capabilities of these sand dams. Results from some previous studies meant that such success was not expected, as several have modelled or measured sand dams to be dry by the end of the dry season. In spite of the success shown in this research, known disparities in sand dam storage and water demands mean that not all sites will necessarily be able to meet abstraction needs. Furthermore, climate change may impact availability in the future.

The research, through geophysics and modelling, has demonstrated that sand dams are in hydrogeological connectivity with the surrounding aquifer. Relatively high rates of lateral seepage mean that sand dams provide a local recharge function. Whilst some interaction was expected, the majority of previous studies have inferred a lower level of interaction than was found. This is due to assumptions of unweathered bedrock underlying the sand dams, which was found to be rarely the case in this thesis. Such recharge behaviour provides holistic benefits by augmenting the local water table: increasing vegetation health and potentially enabling enhanced abstraction further away from sand dam sites.

It is recognised that geophysical investigations can be expensive and require expert engineers. However, the geophysical inversions show a clear distinction in resistivity values between sites with shallow and deep unweathered bedrock, which is supported by probing, augers, and hand dug pits. The thicker the weathered basement layer beneath the trapped alluvium, the greater the volume

of material where water can be lost. This subsequently reduces the storage volume in the alluvium which is readily available for use. Employing geophysical investigations to assess the nature of the subsurface pre-construction would help to identify such sites. Whilst the riverbeds can be assessed for rock outcrops, without geophysics, it would be harder to accurately assess the nature of the underlying basement across the whole site. The results show that in cases of relatively shallow unweathered bedrock, lateral seepage losses can still be substantial. Despite this, identifying and selecting such sites is still beneficial; enabling the holistic benefits of sand dams on water availability within the surrounding shallow weathered basement aquifer to be realised.

Ensuring that sand dams are sited in the optimum location to meet their intended purpose of storage or recharge with optimum site and hydrogeological characteristics is not always easy. If a community who request a dam are not located in the vicinity of an opportune site, then the appropriateness of constructing a sand dam should be questioned. In certain situations, depending on the hydrogeological conditions of an area, other water management techniques, such as RWH tanks, vended water, or a borehole, may be more useful. Just because a community request a sand dam and an NGO are willing to support such an endeavour, does not mean it is the right solution to provide the most sustainable and viable water source to a community. It is also important to clarify where sand dams can make the most positive impact on dryland water security, with results from this study suggesting that sand dams should not primarily be emphasised for domestic water uses.

Limited options, in part due to insufficient funding given to WaSH infrastructure in many countries, means that a sand dam may be the only option. This means that failure rates must be reduced. This thesis adds to the sparse knowledge on seepage from sand dams, which is one failure mechanism. By doing so, it contributes to improving construction and site selection, maximising the benefits from a sand dam. Furthermore, by highlighting their storage capabilities, this study will be beneficial for acquiring funding and support for such structures.

Based on these conclusions, future studies are encouraged to address the disparity between water availability and water use. Are people choosing not to use sand dams to their full potential? Are sand dams, under the current rate of non-functionality, financially viable? These questions are critical for optimising the benefits derived from sand dams and ensuring that their construction is only undertaken in appropriate physical and social contexts.

This thesis supports the use of sand dams to augment water availability in drylands, which is crucial for sustaining livelihoods particularly vulnerable to climate change. Whilst they locally recharge the surrounding aquifer through seepage, they can also provide substantial storage for community use in the river channel. Heterogeneity in benefits and uses, however, means that sand dams must ultimately be seen in their wider context and used as part of a holistic approach to water management in drylands. Sand dams are not universally applicable, with some contexts being more appropriate than others. They should therefore be considered alongside other appropriate technologies. Such small and relatively inexpensive structures will not solve the world's drylands of their water security challenges, but used sensibly, alongside other sources, the evidence presented in this thesis proves that they are a valuable addition.

Appendices

Appendix A Ethical approval letter



27 January 2023

Dear Miss Ritchie ,

Reference: CURES/17734/2023

Project ID: 20468

Title: Assessing the viability of sand dams as a dryland water management technique through an evaluation of water loss pathways

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/17734/2023 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team



12 January 2023

Dear Miss Ritchie ,

Reference: CURES/17690/2023

Project ID: 20417

Title: Assessing the viability of sand dams as a dryland water management technique through an evaluation of water loss pathways

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/17690/2023 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team



4 May 2022

Dear Miss Ritchie ,

Reference: CURES/15435/2022

Title: The causes and subsequent impacts of lateral, longitudinal, and vertical losses of the water stored in a sand dam to the sub-surface environment

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/15435/2022 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team



8 January 2022

Dear Miss Ritchie ,

Reference: CURES/14925/2022

Title: What are the causes and subsequent impacts of lateral, longitudinal, and vertical losses of the water stored in a sand dam to the sub-surface environment?

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/14925/2022 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Published literature review



Sand Dams as a Potential Solution to Rural Water Security in Drylands: Existing Research and Future Opportunities

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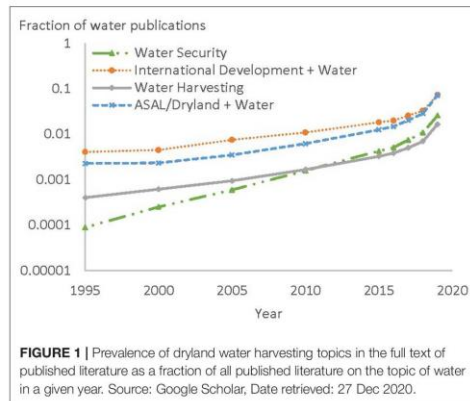
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Sand dams, a rainwater harvesting technique, are small dams constructed across ephemeral streams. During the rainy season, water is stored in the sand that accumulates behind the dam. Sand dams provide communities in drylands with water during the dry season via scoop holes, pools, and shallow wells. Whilst many studies portray sand dams as a positive solution to the growing threat of dryland water insecurity, others highlight their challenges, including poor water quality, evaporation and leakage from some dams, and the contested failure rate and ability of dams to provide water year-round. This article reviews the peer-reviewed and gray literature on sand dams discovered through Scopus and Google Scholar searches, reference lists, and personal contacts. Findings from the collected literature were reviewed and categorized into sand dam hydrology, health and well-being impacts, economic cost and benefits, and water quality topics. In most numerical simulations, sand dams supply water to the local community throughout much of the dry season and exhibit a long-term positive impact on groundwater. Accounts of water storage and loss based on field measurements, conversely, often show that most water is lost due to evapotranspiration and seepage from the sand reservoir rather than community use. Furthermore, the positive impact on local groundwater storage, while variable, is likely seasonal. Sand dams are relatively affordable to build; construction estimates range from 6,000 to 8,500 EUR. However, existing literature suggests that sand dams are likely not a cost-efficient means of supplying water. Nevertheless, successful sand dams can significantly increase water availability and use, whilst reducing traveling time for water collection, subsequently providing a host of secondary benefits from improved hygiene, economic opportunity, and education. Positive impacts, however, are not equally shared and depend on variables, such as abstraction method, catchment, and household location. Furthermore, their water quality is variable, with high microbiological levels detected especially in scoop holes. Whilst sand dams can increase water security and resilience, they may not be an inclusive solution for all. More research is needed to assess the long-term sustainability of sand dams while accounting for the uncertainty of a changing climate.

Keywords: water harvesting, rural communities, arid, semi-arid, water quality, modeling, cost-efficiency, societal impact



1. INTRODUCTION

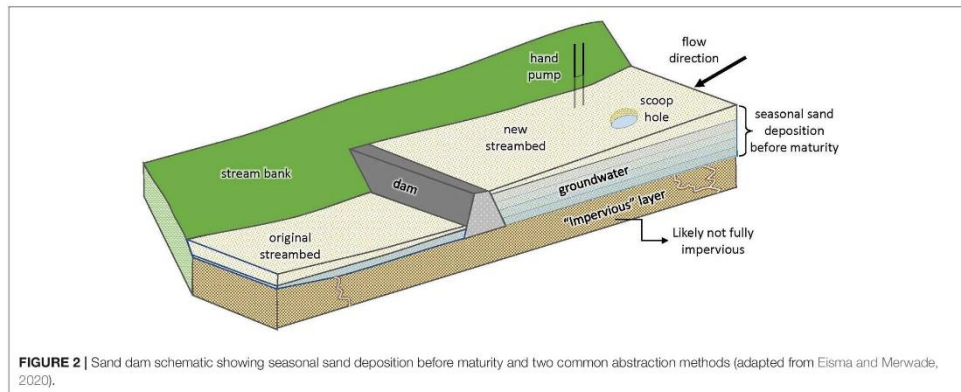
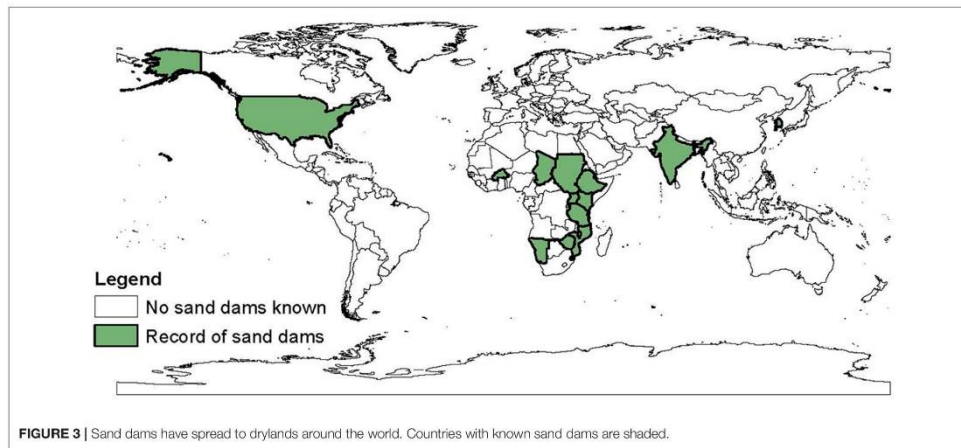
Climate change is exacerbating water stress worldwide. Rural dryland communities already struggling to meet water demand will face increasing water shortages under climate change (Huang et al., 2017). The prevalence of water in the United Nations' 2015 Sustainable Development Goals is a testament to its importance for the global community (United Nations General Assembly, 2015), and public and private entities have responded accordingly. The fraction of all water-related publications dedicated to dryland challenges has exhibited a sharp uptick in the past few years (see Figure 1). Water harvesting techniques, such as roof tanks, dams, and rock catchments are a popular way to tackle climate change-driven increases in rural water insecurity. However, there is often a disconnect between research-based technical guidelines on water harvesting and its implementation, which is largely led by private organizations. This disconnect is likely caused by (1) insufficient consideration of physiographic and sociocultural differences (Yemenu et al., 2014; Lasage and Verburg, 2015), (2) poor alignment between the needs of rural residents and the organizations who study or implement water harvesting techniques (Wanyonyi, 2013), (3) missing data on important indicators in many water harvesting datasets, and (4) the poor public accessibility of the data that does exist (Lasage and Verburg, 2015).

One such water harvesting technique deployed in drylands are sand dams, on which this review will be focused. Sand dams are small dams built across impervious sandy streambeds in drylands that experience infrequent, high-intensity rainfall. Rainfall erodes the topsoil, and surface runoff transports the soil to streams, where it is carried along by ephemeral streamflow. Sand settles behind the dam wall, while lighter silt and clay particles remain suspended and are transported over the dam's spillway. Over time, the sand behind the dam becomes level with the top of the spillway, indicating that the dam has fully matured (see Figure 2). Depending on erosion rates within the catchment, sand dams

can take anywhere from one season to 7 years to mature (Borst and de Haas, 2006). Rainfall and surface runoff infiltrate into the sand dam and are stored in the pore spaces between sand particles. Local communities use the stored water for domestic and agricultural purposes. Many sandy streambeds store water in drylands, but sand dams scale up this potential by increasing the volume of sand in the streambed. In addition to increasing the potential for water storage, sand dams can also help protect stored water from evaporation (Borst and de Haas, 2006; Quinn et al., 2018b; Eisma and Merwade, 2020), increase the quality of stored water (Quinn et al., 2018a; Graber Neufeld et al., 2020), improve overall ecosystem health (Manzi and Kuria, 2012; Ryan and Elsner, 2016; Eisma and Merwade, 2020), and improve the well-being of the local community (de Bruijn and Rhebergen, 2006; Lasage et al., 2008; Pauw et al., 2008; Maddrell, 2010). Despite numerous positive impacts cited in the literature, some studies note that not all sand dams effectively capture and store water (Van Loon and Droogers, 2006; Nissen-Petersen, 2010; de Trinchiera et al., 2015, 2018; Eisma and Merwade, 2020; Ngugi et al., 2020). For a sand dam to perform optimally, well-sorted sand must be the primary reservoir material. When silt and/or clay settle into the reservoir in large volumes, the ability of the sand dam to capture and store water is significantly reduced (de Trinchiera et al., 2015; Eisma and Merwade, 2020).

Spurred by non-governmental organization support, sand dams have spread rapidly over the past 25+ years and can be found in drylands around the world (see Figure 3). However, the overwhelming majority of sand dams have been built in Southeastern Kenya, perhaps due to unique and favorable physiographic features, and thus the majority of sand dam research has also been conducted in Kenya. Researchers have noted sand dams since at least 1968 (Stengel, 1968), but they were the subject of a flurry of studies starting with Borst and de Haas in 2006. The sand dam literature was then relatively quiet for nearly a decade before studies by de Trinchiera et al. (2018) and Quinn et al. (2018a,b) raised new questions and renewed interest. Sand dams are gaining in popularity, but the current literature expresses many opposing viewpoints at least partially influenced by vested interests (Cruickshank and Grover, 2012; Lasage and Verburg, 2015) that need to be analyzed and clarified. Part of this disparity likely arises because research in rural areas of low and middle-income countries is difficult and must contend with many limitations including access, information, and resources. However, research guides foreign and domestic decision-making about developmental priorities and directions, and thus research quality is imperative, especially with a changing climate.

Whilst a number of studies have been published on sand dams, many of these are not peer-reviewed. To date, only a cursory review of sand dam knowledge has been published as part of a larger examination of managed aquifer recharge (Standen et al., 2020). As no specific review of sand dams exists, studies are fragmented, findings are difficult to compare, and results are hard to interpret. A comprehensive analysis of sand dam literature supports better informed future research and implementation practices. More rigorous scientific work on sand dams and other water harvesting technologies must be encouraged to ensure water project managers are better informed when choosing the



most appropriate technology for their target community. This article aims to review and critique the evidence for the benefits of sand dams as a climate change adaptation. It reviews the hydrological capabilities and limitations of sand dams, followed by the impacts of sand dams on the health and well-being of communities, their economic implications, and finally their water quality implications. This study used the search terms “sand dam” and “sand storage dam” in Scopus and Google Scholar to find peer-reviewed and gray literature. Additional references were found from (a) the reference list of key papers, (b) personal contacts, and (c) from general searches in Scopus and Google Scholar to support the main findings. Literature not related to any of the aforementioned themes, referring to other types of sand dams, such as “tailing sand dams,” and whose primary topic was not sand dams were then excluded. This resulted in 54 pieces

of peer-reviewed and gray literature that were reviewed for this article. The literature was categorized into the topics of the article, which doubles as the article structure.

2. SAND DAM HYDROLOGY

Many studies have employed modeling techniques to answer questions related to the functioning of sand dams and their role in local and regional hydrology, climate change, and water management. This section explores the broad categories of water balances and more general hydrological models of sand dams.

2.1. Water Balance

To examine the hydrology of sand dams, a few water balance studies have been conducted. While the water balance equation

varies somewhat among the studies, the general form for a sand dam water balance is as follows (Chow, 2010):

$$F_{in} = F_{out} + ET + Q_A + S, \quad (1)$$

where F_{in} is the flow of water into the reach, F_{out} is the flow of water over the sand dam spillway, ET is the water lost due to evapotranspiration, Q_A is the water lost due to abstraction by community members, and S is the water lost due to seepage through the confining layer, into the streambanks, and around the sand dam.

Calculating the water balance for a sand dam requires collection of various inflow and outflow measurements during an extended field study. As a result, only three studies have collected the necessary data (see Table 1) (Borst and de Haas, 2006; Quinn et al., 2019; Eisma and Merwade, 2020). Of the three water balances, only Quinn et al. (2019) and Eisma and Merwade (2020) provide an analysis of intra-seasonal sand dam water storage fluxes. The assessment presented in Borst and de Haas (2006) is of lumped seasonal fluxes. Despite these differences, the factors considered in the hydrological accounting are similar: baseflow, leakage and/or seepage from the sand dam, evaporation or evapotranspiration, and abstraction (Table 1). Many of these factors have a high degree of uncertainty related to the difficulties associated with determining them *in situ*.

As shown in Table 1, Borst and de Haas (2006) and Quinn et al. (2019) identified the most sensitive factors in their respective water balances, that is those that have the greatest effect on the simulated factor of interest (e.g., abstractable water). The common factor among the sensitive factors is specific yield: the volume of water released from the sand dam by a unit decrease in water table height (Borst and de Haas, 2006). Specific yield is a critical factor in determining a sand dam's water storage effectiveness. It essentially defines the maximum amount of water available for abstraction from a unit volume of sand dam material (Quinn et al., 2019). Yet, specific yield is highly uncertain for sand dams due to the variable composition of reservoir material. Most literature on this topic, and the value used by Borst and de Haas (2006), cites the specific yield of sand dams as 0.25–0.30 (Hut et al., 2008; Quilis et al., 2009; de Trinchera et al., 2018). However, an analysis conducted by Quinn et al. (2018b) indicates that a sand dam specific yield in the range of 0.10–0.16 is more realistic. The discrepancy in expected specific yield and that determined by Quinn et al. (2018b) is caused by the assumption in most studies that sand dam reservoir material is well-sorted sand. Quinn et al. (2019), however, finds that the reservoir material is likely to be poorly sorted, resulting in a significantly reduced specific yield. A sand dam with a lower than expected specific yield will be incapable of providing water to the local community at the expected rate. This impacts not only the sand dam's boon to local water availability, but also their cost-benefit ratio. Future research is therefore needed to identify the range and distribution of sand dam reservoir specific yield.

While evapotranspiration was not identified as a sensitive factor by either Borst and de Haas (2006) or Quinn et al. (2018b), Eisma and Merwade (2020) found that a functioning sand dam loses up to 88% of its stored water via evapotranspiration.

Evapotranspiration is responsible for the majority of water lost from sand dams despite their reputation for protecting stored water from evapotranspiration (Borst and de Haas, 2006; Hut et al., 2008; Lasage et al., 2008; Neal, 2012; Ryan and Elsner, 2016; Quinn et al., 2018b). Similar to lower-than-expected specific yield, high rates of evapotranspiration losses negatively impact the utility of sand dams. Sand dams do reduce expected evapotranspiration losses by up to 19% (Eisma and Merwade, 2020). However, this number is provided relative to evapotranspiration simulated by the Famine Early Warning Systems Network Land Data Assimilation System (FLDAS), rather than calculated with data taken at their study sites. Future studies need to better quantify evapotranspiration losses from sand dams and should also investigate cost-effective methods for further protecting stored water from evaporation.

Infiltration rate has not been studied in the context of sand dams, yet infiltration rate is likely a significant factor in the water balance of sand dams. Due the added challenge of measuring rainfall, surface runoff, and infiltration, water balances at sand dams have largely been initiated after the rainy season has ended, avoiding the need to quantify such parameters in the field (Quinn et al., 2019; Eisma and Merwade, 2020). Despite this, infiltration rates across sand dams likely vary significantly, because infiltration is limited by the hydraulic conductivity of the soil (Chow, 2010). Quinn et al. (2018b) note that hydraulic conductivity at three sand dams likely varies greatly due to highly varied soil profiles. Thus, infiltration rates across sand dams are likely highly variable and dependent upon the composition of the soil upstream of the sand dam. Further research is needed to define the magnitude and range of infiltration rate across sand dams.

Sand dams are built in ephemeral streams, many of which only flow for a few days directly following a rain event. Thus, flow into sand dams is largely limited to a few substantial rain events throughout the rainy season. However, some sand dams do receive lateral seepage from the streambanks during the dry season (Quinn et al., 2019). With the exception of lateral seepage inflows, sand dams primarily lose water during the dry season. The quantity of water supplied to a sand dam also varies spatially, as sand dams constructed in higher order streams will likely receive greater volumes of runoff from upstream catchments. Stream order is weakly correlated to sand dam effectiveness (Ngugi et al., 2020). While spatial and temporal variability of water storage in sand dams is acknowledged in the literature, very little work has examined these variations and developed causation among catchment characteristics and sand dam performance. The work that has been done is largely inconclusive (Beswetherick et al., 2018; Ngugi et al., 2020), highlighting the importance for more research in this area.

2.2. Catchment-Scale Sand Dam Hydrology

While many studies have examined the hydrology of individual sand dams, only a few have assessed the impact of a network of sand dams within a catchment (Van Loon and Droogers, 2006; Aerts et al., 2007; Lasage et al., 2015). The potential of sand dams in drylands was studied using a simplistic modeling strategy that clustered 273 sand dams into 12 representative reservoirs

TABLE 1 | Published sand dam water balances.

Study	Factors considered	Highly sensitive factor(s)	Time step
Borst and de Haas (2006): one sand dam in Kenya	Precipitation, baseflow, leakage, river discharge, evapotranspiration, seepage, abstraction	Reservoir thickness, specific yield, bank slope	Seasonal
Quinn et al. (2019): three sand dams in Kenya	Abstraction, evaporation, lateral flow within the reach, seepage/leakage	Specific yield	Variable, shorter than biweekly
Eisma and Merwade (2020): three sand dams in Tanzania	Subsurface flow, evapotranspiration, and abstraction	Not reported	Weekly

(Van Loon and Droogers, 2006). The sand dams did not store enough water to supply communities throughout the dry season, and the last month of the dry season exhibited the greatest unmet need (Van Loon and Droogers, 2006). Sand dams helped meet 6% of the annual water demand and larger dams were more effective in meeting demand than a greater number of dams (Van Loon and Droogers, 2006). Sand dams decreased downstream flow by 1%. Aerts et al. (2007) and Lasage et al. (2015) studied the ability of sand dams to supply communities with water under future climate scenarios in Kenya and Ethiopia. The results of the two studies vary somewhat based on the climate scenario being tested, but the underlying story is essentially the same. Sand dams will continue to improve water availability for their local communities but will have an increasingly negative impact on downstream flows. With climate change, sand dams will store a higher percentage of discharge (Aerts et al., 2007; Lasage et al., 2015). Aerts et al. (2007) concluded that sand dams currently store between 1.8 and 3.8% of total seasonal runoff, slightly more than the 1% figure concluded by Van Loon and Droogers (2006). The percentage of seasonal runoff stored by sand dams could increase by between 11 and 60%, depending on water use trends, sand dam construction rates, and the severity of climate change (Aerts et al., 2007). Most of this impact is unavoidable however, because climate change has a greater impact on flow conditions than does the presence of a sand dam (Lasage et al., 2015).

While the existing catchment-scale sand dam literature provides an interesting first attempt at quantifying the broader impacts of sand dams, the results must be re-considered given the findings of recent publications. Further research should re-examine sand dam water storage potential considering new estimates for evaporation, seepage, and non-functioning sand dams provided by recently published sand dam studies (de Trinchieria et al., 2018; Quinn et al., 2018b, 2019; Eisma and Merwade, 2020). Research that considers recent findings would better inform water managers on sand dam potential in their communities. Published studies at the catchment scale assume each sand dam stores a given volume of water, and only Van Loon and Droogers (2006) has considered, although conservatively, the impact of non-functioning sand dams. However, recent studies have highlighted the disparity in storage potential (de Trinchieria et al., 2018; Quinn et al., 2019; Eisma and Merwade, 2020), the unexpectedly low specific yield of sand dams (Quinn et al., 2019),

and issues related to non-functioning sand dams (Viducich, 2015; de Trinchieria et al., 2018; Eisma and Merwade, 2020). Furthermore, Lasage et al. (2015) assume only 5% of stored water is lost to evaporation and to seepage, but recent publications cite evapotranspiration and seepage losses up to 88 and 24%, respectively (de Trinchieria et al., 2015; Eisma and Merwade, 2020). It is not clear why Van Loon and Droogers (2006) assume that subsurface evapotranspiration is 50% of surface evapotranspiration, despite subsurface evapotranspiration being highly sensitive to water table depth (Hellwig, 1973). As a last note, both Aerts et al. (2007) and Lasage et al. (2015) employed essentially the same model and the same set of assumptions. Thus, their findings have not yet been verified by other publications. Future research must examine the impacts of sand dams at the catchment scale and under climate change given the recent findings on sand dam storage capacity and water loss mechanisms while employing a wider variety of models, each with their own unique set of assumptions.

2.3. Subsurface and Surface Flow Models

Multiple subsurface and surface flow models have been built to explore how sand dams interact with the local environment. Despite the many flow models developed, most are finite element or finite difference models that have been used to investigate the hydrology of Dam Kwa Ndunda in Kitui County, Kenya (Hoogmoed, 2007; Hut et al., 2008; Quilis et al., 2009). Additional models have been used to study the relationship between surface runoff and sand dam effectiveness (Jansen, 2007) and to study the impact of spillway height and catchment characteristics on sand dam sedimentation (Viducich, 2015). Whilst many models have expanded our understanding of sand dams, their limitations provide opportunities for future researchers, as explored in the following sections.

2.3.1. Subsurface Flow Models

Subsurface flow models have been developed of two independent dams, Kwa Ndunda and Voi in Kenya (Hoogmoed, 2007; Hut et al., 2008) and of a theoretical three-dam cascading system (Quilis et al., 2009), as shown in Table 2. As solely subsurface flow models, these models do not necessarily include rainfall as an input, rather they make assumptions about the impact of rainfall on a key input variable. For example, by assuming groundwater

TABLE 2 | Sand dam subsurface flow models.

Study	Dam configuration	Model configuration	Key findings
Hoogmoed (2007)	One independent dam, Kwa Ndunda	Finite Element (via Triwaco)	<ul style="list-style-type: none"> Seasonal transfer of groundwater between SD and streambank SDs significantly increase groundwater availability, especially in the dry season SD can influence groundwater up to 350 m upstream
Hut et al. (2008)	Two independent dams, Kwa Ndunda and Voi	Finite Difference	<ul style="list-style-type: none"> Mechanical pumping from SD reduces the magnitude and extent of SD impact on groundwater elevations The impact on groundwater elevations increases gradually with time
Quilis et al. (2009)*	Three cascading dams, theoretical	Finite Difference (via MODFLOW)	<ul style="list-style-type: none"> Cascading SDs should be constructed >350 m apart to maximum whole system groundwater impact and water storage potential

*Publication also includes results from Hoogmoed (2007).

recharge is always a certain percentage of precipitation depth (Hoogmoed, 2007), or by assigning season-based values to sand dam reservoir storage (Hut et al., 2008). Further, none of the subsurface flow models consider the impact of subsurface evaporation on sand dam storage and groundwater levels, which artificially increases the impact of sand dams on groundwater levels. Sand dams lose a significant portion of their stored water to evapo(transpi)ration (de Trincheria et al., 2015; Quinn et al., 2019; Eisma and Merwade, 2020), and this loss must be adequately considered in model development.

The results of finite difference models can be heavily influenced by the boundary conditions assigned during model creation. When developing a finite difference subsurface flow model for drylands, modelers must take special care not to artificially increase the inflow of water into the study area. For example, Hut et al. (2008) assigned a constant 1 m of groundwater at one boundary of their study area. Thus, they essentially included a constant inflow of water, because the groundwater naturally flowed from the input boundary toward the sand dam. It is, then, no surprise that their simulations exhibited an increase in groundwater elevations around the sand dam. Hut et al. (2008) likely artificially inflated the impact of sand dams on local groundwater elevation due to their assumption of a constant inflow of water at the study area boundary. In water-scarce regions, ill-suited assumptions during model development can have a significant impact on the findings.

While the previous subsurface flow modeling studies produced insight into the influence of sand dams on groundwater dynamics, many questions remain. Further research is needed to understand the spatial and temporal extent of groundwater impact that results from the added storage in a sand dam. Special attention must be paid to the formulation of water inflow and outflow, being sure not to create unrealistic conditions for dryland hydrology, which has not always been true for the modeling studies reviewed here. For example, the impact of groundwater on surface conditions must be realistic, given that the water table is often many meters below ground level in dryland regions (MacDonald et al., 2012). Further, a subsurface flow model should be developed to study seepage from the sand dam, both through the streambanks and through the impervious layer, noting that the impervious layer is rarely, if ever, fully impervious (Maddrell and Neal, 2012; Eisma and Merwade, 2021). Such a study would inform on the benefits of careful site

selection. Subsurface flow models remain an important tool for investigating the potential of sand dams in drylands, and researchers should continue to refine their use in the study of water harvesting.

2.3.2. Surface Flow Models

Surface flow models are not commonly employed to study sand dams, because sand dams store water underground and are often filled by a single flash flood (Hut et al., 2008). However, surface flow models can provide insight into the optimal design of the dam structure (Jansen, 2007; Viducich, 2015) and their sedimentation process (Viducich, 2015). Similar to findings in Van Loon and Droogers (2006), the MATLAB-based model in Jansen (2007) indicated that larger dams, rather than more dams, should be built to increase availability of water. This is primarily because additional dams are likely to be built in sub-optimal locations, and thus do not capture and store as much water as the existing sand dams constructed in optimal locations. While larger dams built in optimal locations maximize water storage within a catchment, larger dams increase the risk of flooding, erosion, and seepage (Jansen, 2007). Conversely, a greater number of smaller dams minimizes these risks while providing more equitable water access throughout a catchment. The USACE Hydrologic Engineering Center's River Analysis System model developed in Viducich (2015) shows, however, that sedimentation of a sand dam is highly dependent upon spillway height. High spillways are likely to trap fine particles in the sand dam reservoirs, resulting in slower infiltration of water, greater difficulty in abstracting water, and less overall water storage (Viducich, 2015). To combat this issue, Viducich (2015) recommends building the sand dam spillway in stages (Nissen-Petersen, 2011; de Trincheria et al., 2015), noting that as the spillway height increases, the height of each subsequent stage can also increase. Building the sand dam spillway in stages is not unanimously supported (Hut et al., 2008; Ertsen and Hut, 2009), but Viducich (2015) remains the only study to examine this question from a modeling perspective.

The sedimentation process in sand dams remains a point of confusion and contention in the sand dam community (Nissen-Petersen, 2006; de Trincheria et al., 2018; Eisma and Merwade, 2020; Ngugi et al., 2020). Further surface flow models should be developed to study the sedimentation process of sand dams, and the simulated processes should be studied in parallel with a field study and data monitoring. Some uncertainty surrounding sand

dam sedimentation may be due to the inability of the surface models to properly simulate dryland hydraulics and hydrology, hence the need for a field study to verify simulation results. Sedimentation is perhaps the primary reason for sand dam failure and is thus vital to the sustainability of sand dams in dryland water security.

3. HEALTH AND WELL-BEING OF LOCAL COMMUNITIES

A number of studies have explored the health and well-being implications of sand dams largely through interviews, surveys, and observations. This section outlines the overwhelmingly positive primary and secondary impacts that sand dams are recorded as having on communities, as well as the few studies which raise concerns.

3.1. Primary Impacts

Sand dams have been shown to have substantial impacts on the health and well-being of local communities. The primary benefits, as outlined by Pauw et al. (2008) are increased water availability, which allows higher levels of domestic, agricultural and other income generating consumption, and reduced traveling time for water collection. Pauw et al. (2008) compared households with and without access to sand dams in Kitui, alongside dam density, rainfall and agricultural factors to evaluate whether differences observed are actually caused by the sand dams.

Sand dams are said to increase both accessibility and use of water (Nissen-Petersen, 2006; Pauw et al., 2008). According to Maddrell and Bown (2017), each sand dam can directly provide year-round clean water for up to 1,200 people, whilst indirectly benefiting up to 100,000. This claim however, is unsupported by research and should be interpreted with caution. With the storage of water within the accumulated sand, communities with a dam were found by Pauw et al. (2008) to have access to water for an average of 2.5 months longer compared to those relying on water stored solely in the riverbed. Compared to 5 years previous, households with a dam claimed that their source holds water for a longer period of time, and have increased their overall water usage by 321%, compared to a 3.1% decrease for households without. These results are concurrent with the belief that consumption increases with accessibility (Van Haveren, 2004). Nissen-Petersen (2006) similarly promotes the increase in available water, finding that extractable water volume increased within the Mwiwe riverbed post-dam construction. Furthermore, with the construction of a sand dam, time spent collecting water is reduced. Average distance traveled by households interviewed by Pauw et al. (2008) decreased significantly from 2,828 to 812 m, saving, on average, 99.8 min/day, compared to an average distance of 3,501 m for households without, thus increasing disparity (Pauw et al., 2008). Maddrell (2010) and de Bruijn and Rhebergen (2006) found similar time benefits. They report that people spend 30–90 min/day on average collecting water (Maddrell, 2010), and that distance and time decreased from 3 to 1 km and 140 min to 90 min/day, respectively (de Bruijn and

Rhebergen, 2006) with the construction of a sand dam. Whilst all of these results are positive, small sample sizes mean the results are not easily scalable.

As outlined in the hydrology section of this paper, there is contention over the water availability provided by sand dams. de Trinchieria et al. (2015) undertook physical studies on 30 sand dams in Kenya and found at least 67% of them lack the capacity to supply continuous water to even one household during the entire dry season. In a modeling study, Van Loon and Droogers (2006) similarly showed that during the long dry season domestic needs are not met as a result of water shortages in some parts of Kitui County. However, the results of modeling studies are potentially influenced by the hypotheses and assumptions made about the study area and processes during model development. Thus, care should be taken when drawing conclusions from modeling results, because the initial hypotheses and assumptions may not be supported by the current literature (see section 2). Furthermore, the results are significant only for the specific study locations and may or may not be representative of the performance of dams elsewhere. Ngugi et al. (2020) recorded from questionnaires, corroborated by field observations and measurements, that 57% of the dams studied did not have water at the end of the short dry period, with a further 7% having no water at the end of the long dry season. These figures are based on a calculated capacity requirement of n households with 5.98 people/household using 20 L/day. These results are useful for highlighting the capacity of sand dams to improve water security, and could be improved by analysing abstraction data to triangulate results.

These contested benefits may be further compounded by the success rate of sand dams. Very few studies have specifically sought to understand how many dams never fill with sand or break down once constructed, with the values attained by those having done so varying to a large extent. Whilst one study found a 9–11% failure rate (Pauw et al., 2008), Nissen-Petersen (2010) found non-functionality at 90%. Furthermore, de Trinchieria and Nissen-Petersen (2015) found 65% of studied sand dams ($n = 48$) to not be effectively accumulating sand sediment and 29% to be showing severe structural damages. Whilst none of these studies indicate the age of the dams, the reasons of failure were attributed to poor protection of banks, accumulation of silt rather than coarse sand due to rushed construction, rivers bypassing the dam wall and foundation damage, resulting in leakage, filling with very little water or washing away. The general uncertainty surrounding true sand dam success rates significantly limits our understanding of the benefits that sand dams provide. Whilst sand dams may increase water availability and reduce traveling time in certain months and in certain dams, research utilizing larger sample sizes across different seasons is needed to understand any temporal and spatial variation in benefits and whether sand dams are able to provide a year-round water supply.

3.2. Secondary Health Impacts

The two aforementioned primary impacts have been shown to have a plethora of secondary impacts on communities. Closely linked to increased water availability is the improvement in standards of hygiene and nutrition that dams provide as people

report to spend more time washing and cooking (Aroka, 2010). Similarly, Lasage et al. (2008) reported that as a result of time saved fetching water, 29% of households spend more time on domestic tasks including both increasing hygiene as well as cooking meals, both of which will positively impact the health and well-being of a household. This study compared socio-economic developments in the Kiindu catchment, which has three sand dams, to the Koma catchment, which has none. They interviewed 20 households in the former and 19 in the latter on socio-economic changes over the past 10 years from prior to post-sand dam construction, relying on a long recall period. Owing to this improvement in hygiene, alongside the storage of water below the surface and the filtering effect of the sand, the risk of water-borne and mosquito-borne diseases are reduced (Stern and Stern, 2011). This widely cited benefit is supported by Maddrell (2010) who reports that in one Kenyan village, the clinic recorded a 90% reduction in diarrhea post-sand dam construction. There is a risk of sampling bias in these two latter studies, potentially purposefully selecting successful dams, as a result of affiliations with sand dam organizations. Further research would therefore benefit for testing this hypothesis in a more scientifically rigorous way. There is a further risk of confounding factors obscuring the causal effect of sand dams from mere correlations.

Pauw et al. (2008), conversely, found the effect on disease incidence to be both positive and negative. The average number of diseases per household were the same for households with and without a dam (1.80 and 1.79, respectively), with 67% claiming that suffering from disease had stayed constant or lessened with a dam, compared to 76% claiming suffering had increased or stayed constant without a dam. It is unclear from the interviews whether people suffer less because they contract the disease less often or because they are more able to treat it. Less suffering therefore cannot conclusively be attributed to the construction of the dam. Results on disease incidence are evidently inconclusive and inconsistent, highlighting the need for further work to understand the true nature of disease prevalence.

The impact on nutrition may also be felt by the diversification and volume of crops and livestock that can be grown and reared due to increased irrigation, resulting in a more varied and improved diet (Stern and Stern, 2011). Such a phenomenon is cited by Maddrell (2010), who claims that as a result of sand dams, “trees can grow naturally, birds and insects return and farmers can set up tree and vegetable nurseries to diversify diets.” As a result of Kitui sand dams, it has been found that farmers grow an average of 1.39 more, predominantly irrigated crops, than they did before dam construction (Pauw et al., 2008). They also found a significant increase in tree planting amongst households with a dam, who planted an average of 12.87 new trees, compared to 5.0 planted by those without a dam in the past 5 years ($z = 3.30$; $p = 0.00098$), due to high irrigation needs.

3.3. Secondary Well-Being Impacts

Crop diversification is also met with reduced crop failure, further increasing yields and calorific intake (Lasage et al., 2008). This results in reduced vulnerability to future floods and droughts if produce can be stored and traded. This consequently improves well-being as people are less stressed, feeling more secure in

their situation. This has the potential to reduce domestic violence and conflict within the home (Maddrell, 2010). Maddrell (2010) also hypothesizes that conflict may be reduced in the wider community as competition for water between different groups is lessened. This may further be strengthened by the socializing that water collectors can undertake whilst at the sand dam (Chan, 2019). This means of communication that water sources provide may be an important mechanism for improving mental health and well-being.

A sand dam's contribution to community strengthening, however, is an area of contention. Prior to construction, a dam committee is usually set up, enabling NGO and community cooperation in the sand dam building process (Lasage et al., 2008). According to Stern and Stern (2011), there are multiple benefits of this, including local ownership, strengthening of knowledge and skills from accompanying training, and motivation and help exchanged between members in present and future projects (Stern and Stern, 2011). Having said this, Ertsen et al. (2005) believes such involvement does not lead to stronger structures within the community as sand dam committees seem to stop functioning after construction. This may in part be exacerbated by the fact that dams need minimum maintenance, on top of the fact that the technology is largely predefined by the NGO, limiting decision making powers of the community (van Wijk-Sijbesma, 2001). Even if strong community ties are not made as a result of sand dam construction however, the training which a lot of NGOs provide in areas including food budgeting, soil conservation and sanitation can be an added benefit (Ertsen et al., 2005). Despite this training, Borst and de Haas (2006) argues that more education and behavior change initiatives are needed before the full benefits of sand dams can be felt. The uncertainty around the impacts on community structures provides room for further research into the impacts of different water supply interventions with varying degrees of community involvement.

School education is another secondary benefit. Children and women, the primary water collectors, spend less time fetching water. This permits mothers to assume more household tasks, freeing children from these responsibilities and allowing them to attend school more regularly, a mechanism critical for boosting development (Maddrell, 2010). Pauw et al. (2008) received similar responses from interviews: both that children have more time to go to school and that more money is available to send children to school since dam construction. However, the difference in school attendance between the two groups was not found to be significant. More research into the long term impact that sand dams are having on the level of education would be useful.

Finally, the standard of living can be improved by house construction and increased ownership of assets, which sand dams have been shown to facilitate (Lasage et al., 2008). For example, Lasage et al. (2008) found that due to increased water availability, households with dams produce more bricks, which can be used to construct houses in the community. Due to rising economic status, the number of radios has increased by 107% since dam construction, compared to 26% in the Koma catchment (de Bruijn and Rhebergen, 2006). This is just one

of the economic benefits attributed to sand dams. Of course, confounding factors may also be responsible for some of these observed changes. However, regardless, with increased economic opportunity in agriculture, brick and basket making and other professions due to increased mobility and availability of time and water, people's income and therefore well-being and standard of living have the opportunity to rise.

3.4. Heterogeneity in Health and Well-Being Impacts

As the literature illustrates, the majority of health and well-being impacts that sand dams have are positive. There is, however, a suggestion that these benefits are not homogeneous and may differ between household, source type, and catchment (Pauw et al., 2008). Impacts may depend on whether a household is a member of the sand dam committee and therefore allowed to access the water, a household's income, or the proximity with which they live to the sand dam (Ertsen and Hut, 2009; Chan, 2019). For example, Chan (2019) found that at one dam, only members who were part of the construction of the well were allowed to fetch water from the handpump. Local circumstances exacerbate differences between catchments with some sand dams providing enough water to satisfy only domestic needs, whilst other allow for diversification of livelihoods (Strohschein, 2016). The level of impact a sand dam can have on health and well-being may further be affected by volume restrictions set by communities, breakages of hand pumps, time of year, and perceived quality (Chan, 2019). As Aerts et al. (2007) points out, these differences will likely only be exacerbated with climate change.

Owing to limited published research with statistically significant evidence to support the benefits of sand dams, it would be advantageous for future research to analyse in more depth the positive and negative health and well-being impacts of sand dams and how these vary spatially and temporally between different demographic groups. Whilst having identified several benefits attributed to sand dam construction, several studies do not account for other potential changes in the area. It would therefore be beneficial to explore the impact of these confounding factors when studying the influence of sand dams on communities. Finally, conducting studies which rely less on recall and instead utilize real-time accounts of prior to post-sand dam construction would be beneficial.

4. ECONOMIC ASSESSMENT

Sand dams are touted as a low-cost solution to water availability in rural communities and are cited for secondary benefits that increase financial stability in their communities. Surveys and interviews with community members have provided an understanding of the economic impact of sand dams, as discussed in this section.

4.1. Cost-Efficiency of Sand Dams

The cost-efficiency of sand dams in providing water to the community is based on their cost of construction, annual maintenance, expected longevity, and water yield (de Trinchier

et al., 2018). The last of these, water yield, is highly variable and thus introduces great uncertainty into the numbers presented here. Some sand dams fail to supply one household with water throughout the dry season (de Trinchier et al., 2018), while others support entire communities (Borst and de Haas, 2006; Lasage and Verburg, 2015). Construction of a sand dam is generally reported to cost 6,000 to 10,000 EUR (Tuinhof and Heederik, 2002; Munyao et al., 2004; Lasage et al., 2008; Ertsen and Hut, 2009; de Trinchier et al., 2018). Some of this range can be accounted for by the differences in dam height and width. However, dam construction costs in the lower range likely ignore the community's contribution of local materials, labor, food, and housing for skilled tradesmen (Munyao et al., 2004; de Trinchier et al., 2018). Communities and NGOs typically employ a cost-sharing model when planning the construction of a sand dam, wherein the community supplies 44–50% of the construction costs and the NGO covers the remaining costs (Munyao et al., 2004; Cruickshank and Grover, 2012; Lasage et al., 2015). Sand dams are generally accepted to have no annual maintenance costs (Lasage et al., 2008; de Trinchier et al., 2018), and estimates of their lifespan range from 20 to 50 years (Lasage et al., 2015; de Trinchier et al., 2018). Despite the lack of maintenance for the sand dams themselves, the handpumps often constructed adjacent to sand dams require upkeep. Further, the soil beneath the apron of the sand dam frequently erodes, compromising the structural integrity of the sand dam (see Figure 4). Handpumps and sand dam aprons thus need to be considered as maintenance costs in sand dam cost-efficiency calculations. Further, while lifespan estimates for sand dams typically range from 20 to 50 years, additional research is needed to investigate the main factors affecting sand dam lifespan and to provide a more comprehensive analysis of sand dam failure. Assessing the cost-efficiency of sand dams presents many challenges due to high variability in sand dam design, construction, and use.

Attempts to assess the cost-efficiency of sand dams essentially fall into two categories: those where water yield is determined in the field and those where it is assumed based on sand dam reservoir dimensions. Studies in the two categories produce highly disparate cost-efficiency metrics. In most studies where water yield is assumed, the one-time cost of obtaining 1 m³ of water from a sand dam ranges from 0.10 to 0.68 EUR (Mati, 2005; Gies et al., 2014; Lasage and Verburg, 2015). This represents a significant improvement in the cost to obtain water, considering a local price for purchasing 1 m³ of water is ~1.10 EUR (Stern and Stern, 2011). Based on such low water supply costs, sand dams are often concluded to be the most cost-efficient water harvesting technology when compared to rain jars, above ground and underground tanks, open reservoirs, etc. (Mati, 2005; Lasage and Verburg, 2015). However, recent studies have found that sand dams do not store as much water as commonly reported (de Trinchier et al., 2015, 2018; Quinn et al., 2019; Eisma and Merwade, 2020). An in-depth field study of 30 of the 48 sand dams in four different catchments within the Kikumbulyu administrative area in Makueni County, Kenya found that most had an extremely low cost-efficiency (de Trinchier et al., 2015, 2018). Because de Trinchier et al. (2015) found that 67% of sand dams they studied failed to supply water throughout the dry



FIGURE 4 | Mshikamano sand dam near Dodoma, Tanzania exhibiting significant erosion of the apron and left streambank. Photograph taken while looking upstream during the dry season. Photo credit: J. A. Eisma.

season, they calculated the average cost-efficiency of sand dams to be 5,635 EUR per 1 m³ of water yield. Annualizing construction, maintenance, operation costs, and interest over the expected life time of a sand dam, de Trincheria et al. (2018) found the annual water supply to cost more than 30 EUR/household/year. The contrast in reported cost-efficiencies for sand dam water supply indicates that the true average cost efficiency likely lies somewhere between the two extremes of 0.10–5,635 EUR per 1 m³ of water.

The effectiveness of sand dams lies at the heart of the debate concerning their cost efficiency. Water yield exhibits the greatest variability, and therefore introduces the greatest uncertainty into the cost efficiency of sand dams. Most variability in sand dam water yield is likely related to the reservoir storage capacity, reservoir soil texture (sand vs. silt, etc.), and seepage from the sand dam to the streambanks and/or through the streambed rather than catchment-scale parameters like catchment area, mean areal rainfall, or runoff coefficient. Further, as Hut et al. (2008) notes, most sand dams fill with water after a single rain event, so water yield is not necessarily limited by catchment-scale factors. Further research must be conducted to determine the distribution of sand dam water yield. Most studies cite only the average water yield, which is an accurate indicator of water yield only if the data is normally distributed. However, water yield is likely not normally distributed across sand dams (de Trincheria et al., 2018). The average annual water yield of 30 dams was 112.3 m³/year, but the median was only 15.8 m³/year (de Trincheria et al., 2018). Determining the distribution of sand dam water yield is challenging, due to the difficulties in randomly sampling sand dams in a region. Sand dams are often built in small, rural communities that are poorly connected to transportation links, and their locations are not publicly available information. While important to assessing the economic impact of sand dams, simply determining the water yield of sand dams

is a massive undertaking. Additional benefits of stored and leaked sand dam water are not often included in the cost-benefit analysis, despite the water providing many valuable ecosystem services. For example, stored and/or leaked water recharges the groundwater, increases water available to plants, and provides a water supply for wildlife.

4.2. Economic Opportunities in Sand Dam Communities

In communities with a highly functioning sand dam, community members often receive a financial boon as a secondary benefit to increased water security. Constructed in primarily agrarian communities, the additional water stored in sand dams allows for crop diversification, increased irrigation, and livestock raising (Tuinhof and Heederik, 2002; Manzi, 2005; Lasage et al., 2008; Pauw et al., 2008; Cruickshank and Grover, 2012). Increased agricultural activity in sand dam communities leads to a 100% increase in agricultural water consumption (Lasage et al., 2008). Farmers use sand dam water to irrigate ~30% more crops than those without a sand dam (Lasage et al., 2008; Pauw et al., 2008), increasing crop production by 20% (Manzi, 2005). Irrigated crops in sand dam communities can be sold to raise a household's income by up to 40 EUR per irrigated acre (Pauw et al., 2008). Irrigation also supports crop diversification, which provides households with financial stability by protecting against total crop failure (Manzi, 2005; Lasage et al., 2008).

The availability of water and the time saved collecting water are also used to develop non-agricultural money-making ventures, which diversify income and protect against extreme hardship in dry years (Lasage et al., 2008). The most popular of these activities are brick making, basket weaving, laundry services, and beekeeping (Pauw et al., 2008; Ertsen and Hut,

2009; Cruickshank and Grover, 2012; Quinn et al., 2018a). Many also use the time saved collecting water to make ropes and to earn money as casual laborers (Pauw et al., 2008). Communities that pursue brick making not only sell the bricks but also use them to build better homes and more permanent buildings, further improving their standard of living (Lasage et al., 2008; Cruickshank and Grover, 2012).

Overall, the estimated financial benefit to sand dam communities is given in a range from 100 to 215 EUR per year, which represents up to 20% of Kenya's annual per capita gross national income (Lasage et al., 2008; Pauw et al., 2008). To demonstrate the impact of such a growth in income, bicycle ownership in a sand dam community increased by 240% relative to a 10% increase in a nearby non-sand dam community (Pauw et al., 2008). Unfortunately, the financial benefits of sand dams are not equally shared within the community. Users living closest to the sand dams are the most likely to benefit from the additional water and time saved collecting water (Ertsen and Hut, 2009; Cruickshank and Grover, 2012). This discrepancy in benefit is exacerbated further when individuals in the community own a cart or a donkey and can lead to a widening of income inequality (Cruickshank and Grover, 2012). In addition, pastoralists are likely to receive a greater benefit from sand dams than farmers (11.9–13 vs. 0.1–3.1% increase in income), because the additional water reduces the livestock mortality rate while simultaneously supporting herd growth (Gies et al., 2014). Pastoralists make the smallest financial contribution to sand dam construction efforts. In pastoralist communities, NGOs often hire casual laborers to construct the dam to guarantee that the work is completed before pastoralists move on with their herds (Ertsen and Hut, 2009). While functioning sand dams improve the economy of local communities, their benefits are not shared equally among those in the community.

While many studies have developed a foundation for understanding the breadth and magnitude of economic benefits stemming from sand dams, opportunities for further studies remain. For example, study of the economic benefits stemming from sand dams must account for additional training offered by NGOs to some communities. Sand dams in closer proximity to NGO offices are more likely to be visited and receive additional services after their dam is complete (Cruickshank and Grover, 2012). For example, Dam Kwa Ndunda in Kitui County serves as an exemplary sand dam for its sponsoring NGO. The sand dam community is often visited by potential funders and researchers and has been bolstered by additional trainings, such as beekeeping and sunflower production. Conversely, many sand dam communities never receive their promised sand dam maintenance training (Cruickshank and Grover, 2012). In addition, variable sand dam water yield produces unequal economic impact on communities, a reality that remains unexamined. Further research should develop a better understanding of the relationship between sand dam water yield, NGO training opportunities and relationship with the sand dam community, and economic impact.

5. WATER QUALITY IMPLICATIONS

5.1. Water Quality Levels

5.1.1. Electrical Conductivity

Most water quality studies in sand dams focus primarily on salinity and microbiological quality, with Electrical Conductivity (EC) or Total Dissolved Solids (TDS) (derived from conductivity) being the most frequently tested parameters (see Table 3). Multiple studies have found EC/TDS levels which fall below Kenyan (where most sand dam research has occurred) national and global standards (see Table 4).

The majority of papers found a similar proportion of samples falling below quality standards. All studies recorded some samples of high to very high risk, except for Moïse et al. (2019) whose TDS samples all fell below 1,200 mg/L (marginal)—indicating minimal risk. Quinn et al. (2018a) tested EC at 50 dam sites with many pump wells and scoop holes tested twice, improving the reliability of results. Graber Neufeld et al. (2020) undertook similar scientific rigor, randomly selecting 89 sites from 953 sites by a random number generator. Although those selected sites were only from 1990 onwards and built exclusively by two sand dam organizations, bias is limited due to the random selection. Moïse et al. (2019) on the other hand, purposively selected only three dam sites based on water availability, ease of accessibility and presence of at least two modes of abstraction. The very small sample size and selection criteria could explain the lower recorded values of TDS and could have introduced unconscious bias. Similarly, the study by Chan (2019) was funded by Excellent Development and studied only their dams with smart hand pumps, potentially introducing bias into the selection process.

5.1.2. Microbiological

Whilst EC is important in influencing perceptions and water source choice, in isolation it rarely poses a health risk at the values at which it is usually found in water (de França Doria et al., 2009). Microbiological quality, on the other hand, poses a greater threat to user's health. The indicator bacteria, Thermotolerant (TTC) and Total Coliforms (TC), are frequently used measures of microbiological quality in water quality testing. This is because they indicate the potential presence of other more harmful bacteria, which individually are much more difficult to measure (Ferguson et al., 2012). A number of the samples in Table 5 do not comply with WHO standards for microbiological quality (see Table 4). Having said this, the stringent drinking water guidelines of 0 TTC/100 ml is widely understood to be unattainable in many countries (Parker et al., 2010).

These results indicate significant levels of microbiological contamination, which have not been considered by many advocates of sand dams. Having said this, some caution must be taken when analysing these results. For example, Avis (2016) only tested eight shallow wells, whilst Ndunge et al. (2019) only tested five samples—both too small a sample size from which to draw statistically significant conclusions. Furthermore, the technique of testing for TTC was new to the research team, with four of the five positive test hole samples being recorded in the first five samples (Avis, 2016). Whilst digging techniques improved with

TABLE 3 | Levels of EC/TDS measured in different studies.

Study	EC/TDS levels
Borst and de Haas (2006)	EC ranged from below 600 $\mu\text{S}/\text{cm}$ in the rainy season to over 20,000 $\mu\text{S}/\text{cm}$ in the dry season
Kitheka (2016)	EC ranged from 455 to 6,640 $\mu\text{S}/\text{cm}$ in the dry season and 155.9–539 $\mu\text{S}/\text{cm}$ in the rainy season
Quinn et al. (2018a)	Of 83 samples, 25% measured EC above the WHO recommended limit of 1,500 $\mu\text{S}/\text{cm}$
Chan (2019)	Six of 29 samples from hand pumps recorded EC above the WHO recommended limits
Moïse et al. (2019)	All samples recorded TDS of <1,200 mg/L
Graber Neufeld et al. (2020)	Salt content from scoop holes, hand dug wells, pump wells, and surface water in the dry season was poor or unacceptable in 33% of samples

TABLE 4 | Water quality ratings based on total dissolved solids (TDS), electrical conductivity (EC), thermotolerant coliforms (TTC), total coliforms (TC), and turbidity.

Level of risk	TDS ^a (mg/L)	EC ^b ($\mu\text{S}/\text{cm}$)	TTC/ <i>E. coli</i> ^b (CFU/100 ml)	TC ^b (CFU/100 ml)	Turbidity ^a (NTU)
Excellent/no risk	<300	–	0	0	<5
Good/very low risk	300–600	–	1	1–20	5–10
Fair/low risk	600–900	–	1–10	20–500	10–25
Marginal/moderate risk	900–1,200	–	11–100	500–5,000	25–50
Poor/high risk	1,200–1,500	–	101–1,000	5,000–10,000	50–500
Unacceptable/very high risk	>1,500	>1,500	>1,000	>10,000	>500

^a Moïse et al. (2019), ^b WHO (2011).

TABLE 5 | Measures of microbiological quality in different studies.

Study	Microbiological quality
Avis (2016)	83% of test holes complied with WHO guidelines for TTC. 52% of scoop hole samples were recorded as high risk and 24% were very high risk. 37.5% of shallow well samples were free from contamination and the remaining 62.5% had low to intermediate risk
Quinn et al. (2018a)	83% of test holes and 70% of covered wells met WHO standards for TTC, whilst 89% of scoop holes did not, with a median TTC of 159 TTC/100 ml (high risk)
Moïse et al. (2019)	<i>E. coli</i> ranged from <1 to 150 cfu/100 ml in shallow wells and from <1 to 300 cfu/100 ml in scoop holes. 87% of shallow well samples and only 48% of scoop hole samples complied with WHO guidelines for <i>E. coli</i> . 53% of shallow wells and only 6% of scoop holes complied with WHO guidelines for TC
Ndunge et al. (2019)	Three of the five samples had low to intermediate TTC risk and two samples detected >180 cfu/100 ml (high risk). <i>E. coli</i> was detected in two samples at 2 cfu/100 ml (low risk)
Graber Neufeld et al. (2020)	Median level of TTC in surface water, scoop holes and open wells were classified as high to very high risk

time, this initial difficulty may have resulted in an inaccurate estimation of water quality. Furthermore, the use of membrane filtration by Avis (2016) to carry out the microbiological analysis could also have led to false estimates of water quality, because the technique is unsuitable for the high turbidity levels present in most samples. Furthermore, the mode of abstraction is clearly highly influential and will be discussed further below.

5.1.3. Other Physicochemical Parameters

Other physicochemical quality parameters explored in the literature include turbidity, pH, temperature, total hardness (TH), biochemical oxygen demand (BOD), and trace metal elements. On analysis of these findings, turbidity is the most critical physicochemical parameter as turbid water is unpleasant to taste, difficult to chlorinate, and bacteria, viruses and other microbial parasites can hide themselves in the suspended

particles (Moïse et al., 2019). It is recommended by WHO that turbidity should not exceed 5 NTU (WHO, 2017). Table 6 outlines the turbidity values documented in a handful of studies.

Total hardness levels should not exceed 300 ppm in drinking water WHO (2011). Moïse et al. (2019) found mean TH to be 277.38 mg/L. Whilst a maximum hardness of 1,115 mg/L was recorded, 92% of samples complied with WHO recommendations. Ndunge et al. (2019) found similar results with a mean TH 229 mg/L, with two of the five samples only marginally exceeding the standard.

Whilst quality concerns in some localities appear minimal, results from multiple studies indicate heightened levels of EC, TDS, TTC, and TC in certain sand dams, posing several challenges to the local community. As all of these studies focused only on quality once the sand dams had been constructed, further research is needed to understand how physicochemical

TABLE 6 | Measures of turbidity in different studies.

Study	Turbidity
Avis (2016)	25% of shallow wells and 78% of scoop holes had turbidity values of >5 NTU
Kitheka (2016)	Turbidity ranged from 2.5 to 1,000 NTU across different river basins
Quinn et al. (2018a)	Both the median values for covered wells (5–10 NTU) and scoop holes (20–30 NTU) exceeded WHO guidelines. 59% of covered wells and 92% of scoop holes did not meet standards of <5 NTU.
Moïse et al. (2019)	33% of shallow wells and 100% of scoop holes had turbidity values of >5 NTU. Average turbidity in shallow wells was 3.1 NTU, compared to 297 NTU in scoop holes
Ndunge et al. (2019)	Turbidity values ranged from 3.23 to 65.77 NTU, with 60% of samples (3/5) having values of >5 NTU

parameters change from prior- to post-sand dam construction. This would demonstrate whether sand dams are altering the quality of river water, giving a more comprehensive understanding of the impact that sand dams can have.

5.2. Spatial Variations in Water Quality

Water quality in sand dams is spatially highly variable, both between localities and abstraction method. Firstly, EC values tend to be higher in pump wells and sand dams compared to in river scoop holes and surface waters (Kitheka, 2016). Similar trends were found in the Ukambani region of Kenya (Graber Neufeld et al., 2020). Water from pump wells had a median TDS of >1,500 ppm, compared to 500 ppm in scoop holes and surface waters and ~800 ppm in hand dug wells. Measurements of TDS by Moïse et al. (2019) were similarly higher in pump wells (692–1,132 mg/L) than in scoop holes (64–872 mg/L). These heightened levels of EC and TDS in the sand dam pump well may be as a result of ground water recharge, the increased residence time of water entrapped in the dam, and solubilization of minerals from soils, allowing a greater degree of mineral dissolution and therefore a higher value of TDS and EC (Kitheka, 2016).

Anecdotal evidence from Strohschein (2016) conversely suggests that in Kivuna catchment, the riverbed water is considered salty whilst the shallow wells are considered less salty. As quality was not a focus of this study, no data is available, and these comments should therefore be considered with care. The studies in general give little explanation for the changes in EC. As a result of this, and the conflicting results from different studies, further research should focus on both the occurrence and causes of such variation to explore whether any practical steps can be made to mitigate high levels of EC.

Microbiological quality and turbidity are often of a lower standard in scoop holes, surface water and hand dug wells compared with pumps wells. For example, Ndunge et al. (2019) identified counts of *E.coli* only in their scoop hole samples, with levels of fecal coliforms also higher here compared to water samples from taps and shallow wells. Additionally, whilst high fecal coliform levels were detected in surface water, scoop holes, and open wells by Graber Neufeld et al. (2020), significantly lower levels were detected in pump wells. The disparity is further highlighted in studies by Avis (2016), Quinn et al. (2018a), and Moïse et al. (2019) in Table 5. This may be due to the poor sanitary conditions (such as human contact,

animal contact, and water runoff) related to these methods of abstraction (Cairncross and Feachem, 2018). These findings thus suggest that sand dams themselves are fairly effective filters of microbiological contamination, with the source of most microbiological contamination rooted in human error.

5.3. Seasonal Variations in Water Quality

Not only do disparities in water quality occur between abstraction methods, but also between seasons. There is evidence that EC levels are affected by rainfall and stream flow, with the flowing water providing a flushing effect of salts through a system, suggesting that EC levels will be higher in the dry season (Pillsbury, 1981). Borst and de Haas (2006) found the EC of water from sand dams to typically be between 2,000 and 10,000 $\mu\text{S}/\text{cm}$ at the end of the dry season. This compared to values of <600 $\mu\text{S}/\text{cm}$ when the rainy season started owing to much lower levels of EC in rainfall compared to that of groundwater. Similarly, in Makuani, samples taken from areas of lower rainfall and those taken in the dry season were found to have higher average conductivity (Quinn et al., 2018a). Attributing these factors to higher levels of rainfall again is only an assumption and the limited time frame and lack of measurement of confounding factors limits this interpretation. EC improvements with subsequent storms have been demonstrated in a model sand dam scenario, in which a 0.5 m³ sand reservoir was constructed (Hatem kamel and Almula, 2016). The study found that EC decreased by ~80% after five storm events, with TDS also decreasing significantly. The crudeness with which these results have been obtained, however, limits their usefulness when determining the significance and degree of variation seen between seasons. The study is based on a sand dam model built to simulate a sand reservoir, which was filled with sand samples from two different soils. It is, however, unknown where these soils are from, making results limited in explaining real-world, location-specific processes.

Whilst conductivity levels may be higher in the dry season, there is evidence that microbiological quality is lower in the rainy season. Changes in contamination is determined by a balance of factors, such as the input of uncontaminated water (flushing effect), the input of new contamination and the proliferation of existing bacteria (Graber Neufeld et al., 2020). In a study in Niassa, Mozambique, higher levels of TTC were recorded

in both traditional and improved wells during the rainy season (November–March) and in the leadup to the rain (August–September). This later spike could in part be attributed to an increased demand of the wells combined with minimal yield (Godfrey et al., 2006). At sand dam sites, Avis (2016) noted that water running from the soiled surfaces of sand dams into scoop holes likely contributes to contamination here, with this impact likely increasing in significance during the rainy season. Despite general consensus that it is often rainfall which transports coliforms into water sources (Reade, 2001), Graber Neufeld et al. (2020) found no statistically significant difference in levels of coliforms between the dry and rainy season.

Due to some uncertainties around seasonal quality variations, it would be beneficial to undertake an in-depth longitudinal study at various localities. Water quality (EC and microbiological) along with different variables within each location, such as land-use and surrounding geology should be compared. This would enable a better understanding of the causes of quality variations throughout the year.

6. DISCUSSION AND CONCLUSIONS

Quite simply, sand dam hydrology is poorly understood. Most sand dam modeling efforts have effectively explored the hydrology of a perfectly functioning sand dam built into an impervious, homogeneous, and isotropic subsurface. These studies show that sand dams store water for years without drying, raise the groundwater table, and provide water sufficient to support a community in a changing climate (Aerts et al., 2007; Hut et al., 2008; Quilis et al., 2009; Lasage et al., 2015). However, hydrological analyses based on field data collected from a handful of sand dams in Kenya and Tanzania tell a different story. Many of these dams do not retain water throughout the dry season, due to issues with low storage volumes (siltation), seepage (pervious streambed, water flow under or around the dam), and over-abstraction (de Trinchieria et al., 2015; Quinn et al., 2019; Eisma and Merwade, 2020). Whilst this may be the case, sand dams are able to reduce the rate of water loss due to runoff and evaporation, thus extending the duration of water availability through the year (Quinn et al., 2018b; Eisma and Merwade, 2020). Sand dams can also raise the local groundwater, with the extent of impact, however, often limited in space and time (Quinn et al., 2019; Eisma and Merwade, 2020). Functioning sand dams can provide a buffer against climate change-induced increases in water scarcity. However, sand dams likely cannot meet 100% of the predicted needs and are not a one-size-fits-all solution to rural water scarcity.

The majority of sand dam studies identify a positive contribution to the health and well-being of those in local communities. Even if some do not provide a year-round water supply, on successfully filling with sand they are shown to increase water availability (Pauw et al., 2008). Before maturity, a process that can take up to seven years (Borst and de Haas, 2006), sand dams are essentially a traditional masonry dam and store ponded water, increasing local water availability.

However, ponded water is not protected from evaporation or filtered by the sand. Additionally, water accessibility is increased by the provision of a well with a handpump and/or by bringing water closer to settlements, thus reducing water collection times (Pauw et al., 2008). With these impacts comes a plethora of secondary benefits from reduced disease incidence, increased school attendance and improved nutrition (Aroka, 2010; Maddrell, 2010; Stern and Stern, 2011). Whilst impacts are potentially heterogeneous, dependent on factors, such as geographic location and individual sand dam characteristics, their impacts are reported as overwhelmingly positive by the majority of studies.

Highly functioning sand dams provide water to their communities at less than half the cost of buying water locally (Mati, 2005; Stern and Stern, 2011; Gies et al., 2014; Lasage and Verburg, 2015). Thus, sand dams are often cited as the most cost-efficient small-scale water harvesting technology (Mati, 2005; Lasage and Verburg, 2015). However, many sand dams do not provide the expected water yield, which can make them less cost effective (de Trinchieria et al., 2018). In such cases, an investment of up to 10,000 EUR may not significantly increase local water security. For communities with a productive sand dam, their livelihoods are significantly improved. The additional water is used for a wide range of economic activities, such as brick and basket making, irrigating higher value crops to sell, and laundry services (Manzi, 2005; Lasage et al., 2008; Pauw et al., 2008; Cruickshank and Grover, 2012). The increase in economic opportunity raises the local income by up to 215 EUR per capita or 20% of Kenya's annual per capita gross national income (Lasage et al., 2008; Pauw et al., 2008). Unfortunately, these benefits are not shared equally by all, with those living closer to the sand dam receiving the most benefits (Ertsen and Hut, 2009; Cruickshank and Grover, 2012).

The water quality of sand dams, whilst highly spatially and temporally variable, does pose concerns in certain situations. Electrical conductivity tends to be found at higher values in pump wells than in scoop holes and surface water (Kitheka, 2016; Graber Neufeld et al., 2020), whilst microbiological contamination is higher in scoop holes, likely as a result of poor sanitary conditions (Cairncross and Feachem, 2018; Ndunge et al., 2019). These high levels of microbiological contamination, accompanied by such high use of scoop holes are concerning trends across many rural communities, which, along with the underlying causes, need to be taken much more seriously. Other physicochemical quality parameters of note are hardness and turbidity. Whilst turbidity in scoop holes poses a threat, with low compliance of standards, total hardness is less of an issue, with the majority of samples falling within standards. Additionally, higher EC values tend to be found in the dry season, whilst lower microbiological quality persists in the rainy season, resulting in temporally variable threats.

6.1. Critique of the Current Literature

From our review of the literature, several common limitations of current studies have been identified. These shortcomings limit the confidence we can have in their findings regarding the potential benefits and disadvantages of sand dams.

6.1.1. Study Bias

One of the major critiques is in the sampling of sand dam sites. Firstly, sand dams are more often than not constructed by sand dam specific organizations. Whilst this presents benefits in the form of knowledge, time and effort, it can also inadvertently lead to the pursuit of positive results. For example, several of the study authors have direct ties to sand dam organizations, with two such studies being overwhelmingly positive. On the other hand, one is interestingly less so, advocating sub-surface dams instead of sand dams, following several decades of experience in dryland water harvesting techniques (Nissen-Petersen, 2010). Secondly, all of the studies to date have employed non-probability sampling, thus introducing the potential for skewed results. Finally, even when not linked to potential biases, sample selection in many of the studies has been small, limiting the statistical power of results. It is therefore recommended that future studies employ larger sampling sizes. It would also be beneficial for a study at one point to include all constructed dams in a sampling frame. This would ensure no bias toward selecting favorable sand dams for study and would also provide insight into the success rate of dams, which few studies have addressed.

Most published studies focus on Kenya, displaying a distinct lack of geographically diverse study sites. With many optimum sites, Kenya has seen by far the most sand dams constructed in recent years. This has unsurprisingly made it a fitting country for sand dam research. Having said this, sand dams do exist outside of Kenya. The current lack of research in other countries limits our understanding of the applicability of sand dams elsewhere, however, and hence minimizes confidence and subsequent investment in sand dams in such places. Carrying out studies in localities outside of Kenya, both with known and unknown sand dam potential is therefore encouraged.

6.1.2. Questionable Methodologies

Other limitations in a number of the reviewed studies stem from less than optimum methodologies. For example, most interviews, surveys and participatory methods have relied on recall, with no studies gaining real-time data. Whilst real-time data collection is very often impractical, relying on recall can significantly reduce the accuracy of results, especially when collecting data from many years previous, prior to sand dam construction for example. Other studies have lacked scientific rigor, with, for example, no statistical analysis, crude data collection methods and sampling techniques, and a lack of data to support claims. Whilst this is by no means the case for all studies, it is important to note. Finally, with regards to methods, is the prevalence of cross-sectional studies. Whilst a handful of studies conducted longitudinal studies, the majority collected data at only one point in time. This is limiting due to missed trends in seasonal variations and future studies should strive to collect data across seasons and in real-time, if feasible.

Furthermore, results from sand dam field studies often do not agree with modeling results, because the assumptions made to develop the models are questionable. For example, most sand dam models assume a specific yield of 0.25–0.30. However, field studies indicate that the specific yield of sand dams is likely around half of that (Quinn et al., 2018b). Further, sand

dam models assume the structure is built into an impervious streambed, but this is likely rarely the case. Identifying the imperviousness of a streambed is challenging under the best circumstances but infeasible in the rural drylands where sand dams are built. As much as possible, sand dam models should reflect the findings of field studies investigating the hydrology of sand dams.

6.2. Further Research Needs

The assessment of current knowledge on sand dams presented above highlights the need for further research, firstly to provide evidence to support or counter existing uncertainties and secondly to conduct studies on which no data exists, ensuring that some of the limitations identified are addressed. Very few studies have looked at the future role of sand dams under climate change. Under increasing pressure to improve water security as a result of climatic uncertainty, further studies on sand dams must highlight their potential benefits and shortcomings in improving water security so that informed decisions can be made about their sustainability.

Many gaps remain in our understanding of sand dam hydrology and the opportunities that sand dams present for increased water security. Studies should be conducted to better quantify evaporation losses and to identify cost-effective ways to protect stored water from evaporation. Additionally, an extensive field study is needed to examine the spatial and temporal extent of groundwater impact that results from added storage in a sand dam. If sand dams do significantly recharge the local groundwater table, such a study would explain the dynamics of the recharge process and provide insights into how sand dams function within their local ecosystem. Further, studies should employ a greater variety of models to examine the effectiveness of sand dams under climate change, incorporating varied assumptions and considering recent findings when setting parameters.

Finally, a need for studying sand dam sites pre- and post-construction has been identified. Whilst a lot of work has been done on appropriate site selection, no studies have measured parameters before and after construction in real-time. Useful data to collect would include water quality, water availability, wealth, and education. By measuring such parameters pre- and post-construction in real time, the impact that the dams are having on water quality, the health and well-being of local residents, and their ability to cope with climate change could be better understood.

6.3. Uncertainty and Sand Dams With a Changing Climate

The limitations of the current literature and gaps in our knowledge make it difficult to unequivocally support sand dams as the most effective climate change adaptation for rural dryland communities. Their role in helping communities to cope in a changing climate and increasing water stress cannot yet be fully defined. At best, sand dams revitalize communities by increasing water availability, health, and economic activity. At worst, sand dams are expensive man-made waterfalls. These two extremes are unlikely to be affected by climate change, and sand dams

are likely to continue providing a positive, but varying, impact on their local community. Current climate change projections in East Africa indicate a trend toward increased rainfall that is concentrated in fewer, more intense events (Bank, 2013). This will exacerbate the current condition in most of rural East Africa, where communities lack the infrastructure to capture and store water for use between rain events and during the dry season.

Such a pattern of rainfall will have far reaching impacts, because much of the economic activity in rural communities relies on the use of water. For example, most agricultural land in sub-Saharan Africa is primarily rainfed. Infrequent rainfall will increase the likelihood that crops will experience extended periods of water stress, which will decrease crop yield (Biazin et al., 2012). Reduced crop yield will not only impact the food security of rural communities but will also significantly reduce their annual income, which is typically generated from selling excess crops to the market. Sand dams can successfully improve rural water availability but are often not reliable enough to be the sole solution employed by rural communities facing decreased water access as a result of climate change. Communities would benefit from a multi-modal approach that relies on a combination of water harvesting infrastructures to increase climate change resilience. With a changing climate, sand dams will increasingly provide unequal access to water for many communities. As shown in the climate change analysis by Aerts et al. (2007) and Lasage et al. (2015), sand dams will continue to improve water availability in local communities but may have an increasingly negative impact on downstream flows. With a reduced frequency of rainfall events, sand dams may store a higher percentage of seasonal runoff thereby reducing water security for downstream communities (Aerts et al., 2007).

Climate change also has implications for the quality of water in sand dams. Warmer temperatures may increase the rate of evaporation from sand dams, potentially increasing the salinity of the stored water. Increased salinity not only reduces the palatability of water but will also negatively impact crop production (Grattan, 2002). Whilst the microbiological quality

from scoop holes is often low, this is often due to poor sanitary conditions. The sand dams themselves, however, are largely able to filter much of the microbiological contamination in the water. More extreme weather, however, has the potential to improve conditions for the growth of bacteria, increasing the risk of water-borne illnesses (Charron et al., 2004).

Sand dams certainly have widespread positive impacts for many communities, and these benefits will continue despite a changing climate. However, sand dams also leave some households behind—due to unequal benefits within, and across communities (Ertsen and Hut, 2009; Cruickshank and Grover, 2012), most notably in downstream communities and in those with non-functioning sand dams. Further work is needed to improve both the science of sand dams and the water management practices employed by sand dam communities to maximize their potential as a climate change adaptation.

AUTHOR CONTRIBUTIONS

HR and JE contributed equally to writing the manuscript and share first authorship. AP contributed by reviewing this work and providing the expert knowledge. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix B: Published literature review: Sand Dams as a Potential Solution to Rural Water Security in Drylands: Existing Research and Future Opportunities in Frontiers in Water

Appendix C Published version of chapter 4

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RESEARCH



Sand dam contributions to year-round water security monitored through telemetered handpump data

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Abstract Sand dams are a form of rainwater harvesting, prolific in arid and semi-arid lands. Water is provided partly via handpumps, which, as the only improved method of abstraction from sand dams, are important for drinking water security. Accelerometers and cellular transmitters were fitted to 30 handpumps by the Africa Sand Dam Foundation (ASDF) in 2019 to monitor the use and reliability of the handpumps by recording hourly water volume abstracted. Data from April 2019 to October 2021 for 26 of these sites, alongside qualitative data, were analysed and each handpump's contribution to year-round water security was explored, focusing on the long dry season when water supply from other sources is compromised. Abstraction was over 20 times higher in the long dry season than in any other season, and at sites with higher salinity, higher livestock use, and larger dam wall area. At 21 wells, abstraction was still being recorded at the end of at least one long dry season; however, high spatial and temporal heterogeneity between pumps and seasons means that not all sand dams deliver reliable water supply year-round. Quantifying the contribution that sand dams make to water

security is crucial for understanding their resilience against a changing climate and can aid decision makers when choosing the most appropriate water management technique. Knowledge of temporal and site heterogeneity in abstraction can inform when other water sources need increasing and can help with sand dam design optimisation. Overall, our results indicate the positive contribution that sand dams make to year-round water security through the water that is abstracted through handpumps.

Keywords Dryland · Rainwater harvesting · Telemetry · Arid-semi-arid land (ASAL) · Abstraction · Kenya

Introduction

Drylands, or arid regions, are home to one-third of the world's population but face severe threats to water security, resulting in a deficit between supply and demand (Davies et al., 2016). As one of the most sensitive areas to climate change (Huang et al., 2017), challenges related to water supply are increasing (Lian et al., 2021), meaning resilient, holistic approaches to water management are crucial. One such technique, popular in certain dryland settings, is sand dams.

Sand dams (Fig. 1A) are small, concrete structures constructed across ephemeral streams. Alluvial sand accumulates behind the walls, in which water collects

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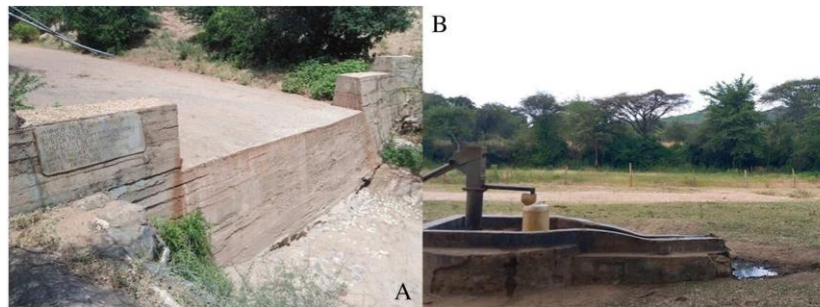


Fig. 1 **A** Sand dam, comprising a concrete dam wall with a natural accumulation of sand behind it forming the sand aquifer; **B** hand-pump in the upstream bank of a sand dam

in the rainy season and is stored for use in the dry season (Neufeld et al., 2021; Pauw et al., 2008; Stern & Stern, 2011). They are indigenous structures that are found in sub-Saharan Africa, southern Africa, Asia, and North America (Ritchie et al., 2021). The water is used for domestic consumption, agriculture, livestock, and other water-consuming projects such as brickmaking (Beswetherick et al., 2018; Cruickshank & Grover, 2012; Lasage et al., 2008; Parker et al., 2022; Pauw et al., 2008; Ritchie et al., 2021; Tuinhof & Heederik, 2002). The needs of individuals using a sand dam vary, but in general the dams must rarely provide for entire year-round water needs, with other sources such as boreholes, rainwater harvesting (RWH) tanks, kiosks, surface water, springs, and piped water supply used (Lasage et al., 2013; Neufeld et al., 2020; Strohschein, 2016). Whilst people rely more on RWH tanks in the rainy season (Adekalu et al., 2002; Boelee et al., 2013; Elliott et al., 2017; Özdemir et al., 2011; Shaheed et al., 2014), sand dams can be a useful source of water in the dry season when other sources run low or are unavailable (Maddrell & Neal, 2013; Neufeld et al., 2020; Strohschein, 2016).

This region is characterised by four seasons: short dry season (January–February), long rains (March–May), long dry (June–September), and short rains (October–December) (Camberlin and Wairoto, 1997; Musyimi et al., 2023; Nganyi, 2009), with an average annual rainfall from 1981–2021 across the sites of 286 mm and 375 mm in the long and short rainy seasons respectively (derived from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)) (CHIRPS, n.d.).

Whilst the area receives reasonable rainfall, much of it is lost as runoff, leading to water deficits. According to Augustine et al. (2014), the average person in Makueni uses 19.55 ± 0.343 L of water per day.

Sand dams are most common in Kenya, where 84% of land is arid or semi-arid and a 31% gap between available water resources and water demand is anticipated by 2030 (Davies & Gustafsson, 2015). Surface and unimproved water sources are used by 19% and 9.8% of people, respectively, endangering drinking water quality and future water security (WHO & UNICEF, 2022). However, the prevalence of streams and rivers with high coarse, suspended sediment loads offers opportunities for sand dam construction (Hut et al., 2008; Mutati et al., 2018; Vidulich, 2015).

There is uncertainty around the contribution that sand dams make to year-round water security. Ngugi et al. (2020), van Loon and Droogers (2006), and de Trinchiera et al. (2015) found that many dams do not have the capacity to support water needs throughout the entire long dry season in Kenya. The former two studies are located in the Tiva catchment (in the west of Kitui), whilst the latter is located in Makueni. Through surveys, Ngugi et al. (2020) found that almost 50% of 116 dams did not have water by the end of the long dry season, whilst de Trinchiera et al. (2015) found that 67% of 30 dams did not supply water to even one household during the entire dry season. From modelling, van Loon and Droogers (2006) found an unmet demand from July to September. Borst and de Haas (2006), Quilis et al. (2009), and Hanson and Nilsson (1986), on the other hand, cite the opposite. The former two studies are in the

Kiindu catchment (a small catchment near Kitui town (Ertse & Ngugi, 2021)), whilst the latter is based in the Hararghe region of Ethiopia. Hanson and Nilsson (1986) and Quilis et al. (2009) cite, from measurements and modelling, respectively, that the dams are full several months after the end of the rainy season and can effectively increase water availability throughout the dry season. Borst and de Haas (2006) studied a 2-km stretch of river comprising five dams and found from a water balance that 11m^3 is now available per day in this area from March to October, compared to 2m^3 before dam construction, with 8m^3 currently being used per day. Given the geographical similarity between most of the studies, location is not assumed to be the cause of differences in water availability. No studies to date have specifically quantified annual water abstraction from sand dam handpumps (Fig. 1B), creating uncertainty around the usefulness and financial viability of sand dams.

Quantifying the volume of water abstracted from sand dams via handpumps is key to understanding sand dam's contribution to water security, and their potential resilience and sustainability against a changing climate. Whilst abstraction volumes may be linked to storage, other variables, including convenience, quality, and the use of other sources can impact abstraction. In response, this study seeks to understand the contribution that sand dams make to year-round water security by studying abstraction patterns, from sensor-derived handpump data and the characteristics of sand dams, from interviews and empirical data, which may be impacting these

patterns. The study is the first of its kind at sand dam sites to use abstraction data which avoids reliance on recall and assumptions made in modelling, and which spans a continuous 31 months rather than providing a snapshot in time. It is hypothesised that sand dams improve communities' year-round water security by sustaining water availability in the dry season. Proving or disproving this is crucial for understanding sand dams' level of use, acceptance, and financial viability. It will help to inform future water management interventions and to ensure that users are serviced with an improved supply throughout the year.

Materials and methods

Study context

The study location was rural areas of the Makueni and Machakos counties, in Southeast Kenya (Fig. 2), and the project was conducted in partnership with Sand Dams Worldwide (SDW) and the Africa Sand Dam Foundation (ASDF). This area was chosen due to large investment in sand dam construction.

Data sources

To quantify the contribution that sand dam handpumps make to year-round water security, three data sets were used: sensor-derived hourly abstraction data, CHIRPS rainfall data, and interview and observational data.

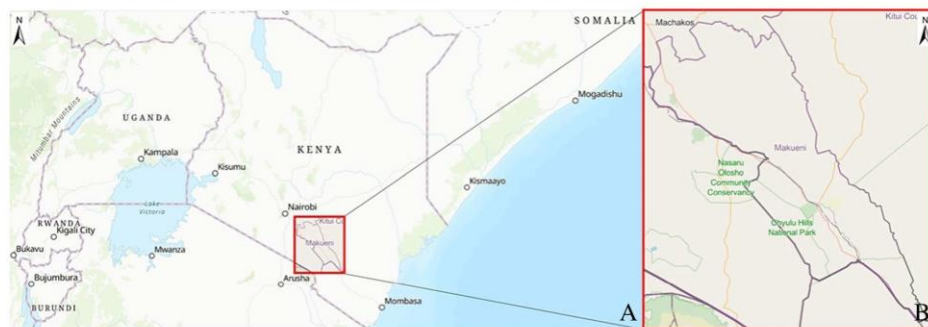


Fig. 2 **A** Map of Kenya at a 1:9,000,000 scale, **B** map of Makueni and Machakos counties, Southeast Kenya at a 1:1,500,000 scale at A4, where the study sites are located (processed using ESRI® ArcGIS Pro™)

The handles of thirty sand dam handpumps at thirty different sites were fitted with waterpoint data transmitters (WDT). The WDT consists of an integrated-circuit-based accelerometer, a microprocessor, and a GSM (global system for mobile communications) modem (Thomson et al., 2012). The accelerometer measures handle movement by sensing movement in X, Y, and Z planes to produce three analogue outputs proportional to the acceleration sensed along that axis. The microprocessor then takes the acceleration data in order to calculate pump handle tilt angle, which is monitored to produce a count of the number of strokes the pump handle has moved over a given time period. The relationship between stroke length and number of strokes was used to then estimate the volume of water abstracted (Thomson et al., 2012).

The data is then transmitted as a short message service (SMS) via the GSM modem (Thomson et al., 2012). Thomson et al. (2019) previously calculated the estimated volume abstracted (derived from the conversion of pump handle movements from the WDT) to give a $\pm 15\%$ accuracy against measured volume abstracted.

Each site fitted with a transmitter was selected due to (1) a strong cellular network signal so that the accelerometers can transmit data (which are converted to abstraction volume) through the mobile network and (2) the handpumps being used daily in order to provide continuous data (Chan, 2019). ASDF visited each site to verify daily usage; however, many areas with high usage had no network coverage, meaning that some sites with lower daily usage with network coverage were selected. Twenty-six of these handpumps were selected for this study based on data availability and continuity. The data spans from April 2019 to October 2021.

CHIRPS data, a 35+-year quasi global rainfall data set, was used to assess rainfall levels at the 26 dams. CHIRPS combines data from models, real-time observing meteorological stations, and 0.05° (5km) resolution infra-red satellite data to estimate daily precipitation (Funk et al., 2015). Mulungu and Mukama (2023) evaluated the accuracy of CHIRPS, finding it to correlate well with ground rainfall observations on a monthly timescale, but less well on a daily scale with Pearson's correlation coefficients of $r > 0.7$ and $r > 0.5$ respectively. Although CHIRPS data is less accurate in dry than moist conditions, with light precipitation events found to

be underestimated and heavy precipitation events overestimated, it has been found to be more suitable than other products for small-scale studies (Bai et al., 2018; Liu et al., 2019).

Characteristics of each dam were collected during fieldwork by Chan (2019) and provided by ASDF and SDW. Interviews and measurements were conducted at 30 sand dam communities, chosen due to the presence of a WDT (26 of which abstraction data are available for), from June 20 to July 12, 2019 (Appendix A). This part of the study gained ethical approval through the Cranfield University Research Ethics System (CURES) CURES/8640/2019. Subsequently, 203 semi-structured interviews were conducted with the assistance of a translator, in the homestead or at the handpump. Participants were selected for interview using a snowball sampling method, on the basis that they used the handpump in question. Questions were centred around volume usage and ease of access to handpumps. The interviews were intended to identify the frequency of handpump usage and to determine which factors may cause people to use other water sources over handpumps. Water samples were taken at each handpump using a plastic cup, in which electrical conductivity was tested using a hand-held probe.

Variables collected in fieldwork included perceived salinity (% of interviewees perceiving water as saline), abstraction limits (inc. only selling to members, limited number of jerry cans/p/day), livestock use (% of interviewees using the handpumps for livestock), whether the dam is said to have ever run dry, presence of rain-water harvesting tanks (% of interviewees with tanks), and actual salinity ($\mu\text{S}/\text{cm}$). These variables were chosen based on knowledge regarding possible reasons for the use of such wells (Chan, 2019). Variables provided by ASDF and SDW included area of vertical face of dam wall (area: height $\times$ length of wall (m^2)), distance (average distance of round trip to handpump (km)), and user numbers. These were analysed using two models to provide insight into differences in abstraction between sites.

Data analysis

The rainfall data was analysed in Google Earth Engine (Gorelick et al., 2017). A single CHIRPS cell was selected for the coordinates of each dam to give a time series of daily rainfall data across the study period. The data from each site was averaged

across the study period and from 1981 to 2021 to also give long-term average rainfall.

Some abstraction data was missing due to signal and battery failures. Hourly abstraction of 0L (handpumps not used) was differentiated from missing data, which was represented by NA or an excluded data point. The raw hourly data was collated into daily, weekly, monthly, and seasonal data for the analysis.

To account for the missing data, all days with any missing hourly data were excluded so that total daily abstraction was based on a complete day. Following this, specific inclusion criteria were developed for different abstraction data sets depending on the analysis:

- To analyse patterns of abstraction, daily, monthly, and seasonal (L/day) data sets were used. All data were used, apart from four outliers at Wikwatyo of >14,000L/day which were removed where necessary for clarity in figures.
- To analyse the relationship between sand dam characteristics and abstraction volume, median monthly abstraction per person (L/person/day) was used. Only handpumps with data for all variables in the models were included.
- To analyse abstraction patterns in the long dry season, median weekly abstraction per person (L/person/day) was used. Only handpumps with >4 days' worth of data available for the last week of September in at least 1 year were used.

These data sets were used to assess the contribution that each handpump was making to year-round water security. The data were coded and analysis performed in R Studio (RStudio Team, 2020) and Stata (StataCorp, 2021).

Descriptive and inferential statistics were used to explore general patterns of abstraction, both spatially and temporally. A Friedman test, a non-parametric alternative to a one-way ANOVA test, used when measurements of a group of subjects are taken over time, was used to assess statistical difference in the median daily abstraction between seasons (L/day). Following a detrending of the data, total monthly abstraction was compared to total monthly rainfall at each site, using Spearman's rank correlations (non-parametric version of a Pearson test), to assess whether monthly abstraction varies significantly with rainfall.

To explore which characteristics may impact abstraction, two random effects regression models were used, as such models can handle panel data and are used to fit a relationship between two or more variables (Park, 2011). A Hausman test indicated the merits of a random over a fixed effect model, and the dependent variable (median monthly abstraction (L/day)) was log transformed, enabling assumptions of a linear model to be met. Median rather than mean abstraction was used due to the skewness of data. A monthly timescale was used to assess seasonal variation over the year. Significant (p) independent predictors of outcomes were assessed at $p < 0.05$, <0.01 , and <0.001 . The first model included the independent variables: month, site, actual salinity, area of dam wall, livestock usage, abstraction limits, and the proportion of interviewees with a RWH tank. The second model additionally included distance. These variables were chosen for exploration purposes and due to previous research findings (actual salinity, livestock use, RWH tank, and distance (Chan, 2019; Kelly et al., 2018; Rahman et al., 2017; van Schalkwyk, 1996)). Variables were dummy coded as categorical variables into two groups of roughly even sizes centred around the average.

Finally, analysis in the last full week of September (end of the long dry season) assessed whether handpumps were providing at least sufficient drinking water by this point. Due to the necessity of an improved source of water for drinking, the handpumps were classified based on a median weekly abstraction of 2L/p/day and 4L/p/day in the final full week of September, based on the minimum drinking water requirement cited by the World Health Organisation (2016) in regular and hot climates respectively. This was done to assess whether the handpumps could independently meet drinking water needs, in case no other water source was available. The handpumps were sorted into three groups based on a median weekly abstraction of 2L/p/day (the lower cited minimum drinking water requirement (World Health Organisation, 2016)). Due to the 15% uncertainty in the data, the groups were as follows: <1.7L/p/day not providing sufficient water, 1.7–2.3L/p/day potentially providing sufficient water, >2.3L/p/day providing sufficient water. Any handpumps providing >4.6L/p/day, derived from the minimum drinking requirement in hot climates (World Health Organisation, 2016) with a 15% uncertainty, are marked with an X in Table 3.

Values were based on per person abstraction using an average of 3.7 residents per household (Knoema, 2019). However, due to differences in cited household size, with Augustine et al. (2014) citing an average of 6.15 residents per household in Makueni, any handpumps with $>2.3\text{L/p/day}$ still being abstracted when using a household size of 6.15 are marked with a 0 in Table 3.

Results

Rainfall

Average monthly rainfall across the 26 study sites for the duration of the study period (April 2019–October 2021) displayed the recognised Kenyan trend of two rainy and two dry seasons. Long-term average yearly rainfall across the 26 study sites from 1981 to 2021 was 760mm. Yearly rainfall for 2019, 2020, and 2021 was 1035mm, 996mm, and 726mm, respectively, highlighting 2019 and 2020 as wetter than average (CHIRPS, n.d.).

However, on a seasonal level (based on literature derived seasons), the long rainy seasons in 2019 and 2021 were drier (160 mm and 264 mm respectively) than the long term average (286 mm), whilst 2020 was wetter (438 mm). This is in comparison to the short rainy season, which in 2019 was over two times greater (797 mm) than the average (375 mm), whilst 2020 and 2021 were slightly drier (332 mm and 369 mm respectively) (CHIRPS, n.d.).

Patterns of daily abstraction

Spread of daily data

Across the months in which each handpump transmitter was live, the amount of missing daily data ranged from 5.8% at Woni 15 to 75.4% at Woni 16. Seven handpumps had $>50\%$ of data missing, whilst twelve had $<25\%$ of data missing. Not all transmitters were operational from April 2019 to October 2021, making it an unbalanced data set. The data set of daily abstraction showed a non-normal distribution, with a high positive skew to the right (skewness = 3.58, indicating a

high proportion of small values). Of 11,610 data points, there were $n=840$ counts of 0L abstraction, whilst most values (1,307) lay between >0 and 250L/day.

Heterogeneity between sites

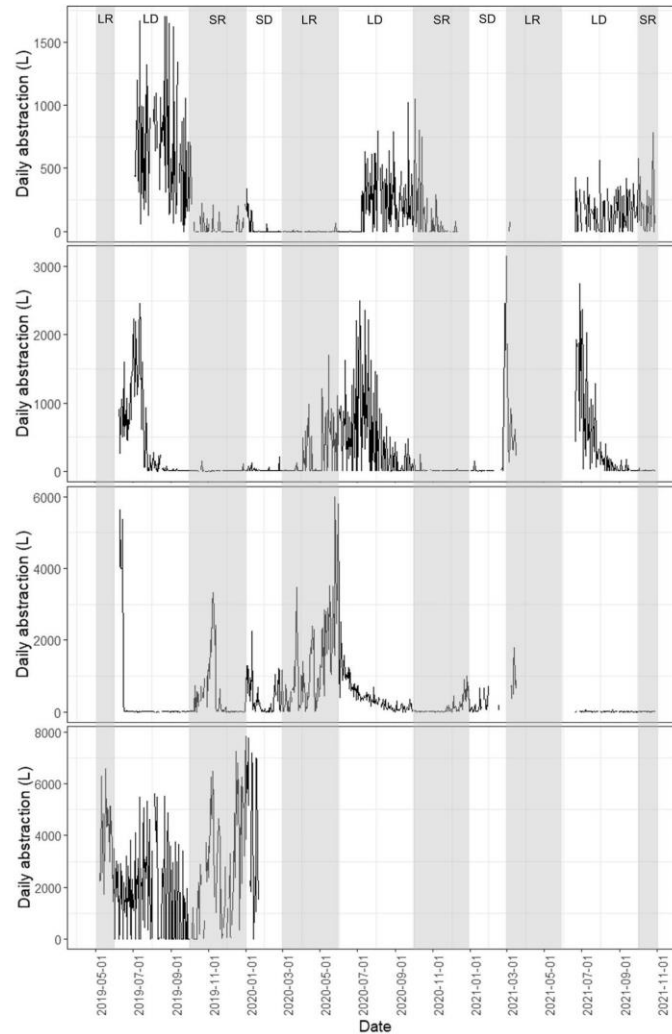
There was heterogeneity in daily abstraction patterns and volumes between handpumps. Four sites (Fig. 3) have been used to represent the main patterns observed. Most handpumps saw peaks of abstraction in the long dry season ($n=17$) (Fig. 3A), whilst some also saw peaks in the short dry season ($n=5$) (Fig. 3B). Others saw additional peaks in the rainy season ($n=11$) (Fig. 3C), whilst some showed similarly high levels of abstraction across the year with no distinct peaks ($n=3$) (Fig. 3D). Due to this heterogeneity between handpumps, median daily abstraction, although 95L overall, varied greatly between individual sites from 2L at Ikanga to 2962L at Woni 16 (Fig. 4).

Heterogeneity between seasons

Handpump use was heterogenous between seasons (Figs. 5 and 6). Whilst the range of abstraction data across the handpumps was not dissimilar in each season, the median abstraction was highest in the long dry season (444 L/day) compared to 13 L/day in the short dry season (Fig. 5). A Friedman Test indicated a significant ($p = 0.0145$) difference in median daily abstraction between seasons (L/day) amongst individual sites.

Median monthly abstraction averaged across all sites showed a peak in the long dry season (August in 2019, July in 2020, and September in 2021). There is generally a decreasing trend in abstraction towards the end of the long dry season in 2019 and 2020. Lower levels of abstraction were observed throughout the rest of the year, with the lowest occurring at the end of the short rainy season in 2019, in the short dry season in 2020, and at the end of long rainy season in 2021 (Fig. 6). Spearman's rank correlations of total monthly abstraction compared to total monthly rainfall at each individual site indicated a significant negative correlation at four sites and a positive correlation at one: Athiani ($r=-.45$, $p=0.038$), Kithunthi ($r=-.52$, $p=0.007$), Mapatano 17 ($r=-.48$, $p=0.010$)

Fig. 3 Daily time series of abstraction at sites **A** Ikanga, **B** Mapatano 18, **C** Makutano, and **D** Woni 15. Rainy season is shaded. LR, long rainy; LD, long dry; SR, short rainy; SD, short dry season

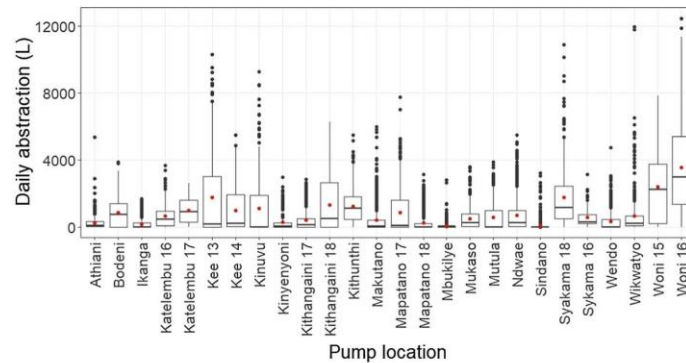


Mbukilye ($r=-.64$, $p=0.0003$), and Wendo ($r=-.74$, $p=2.15e-05$), with the four latter sites indicating significantly higher monthly abstraction when rainfall is lower. Most of the other sites also show negative correlations, as shown in Fig. 6, displaying median monthly abstraction and precipitation across each site.

Relationship between sand dam characteristics and abstraction volume

In order to assess whether any sand dam characteristics or individual behaviours were influencing abstraction, two random effects regression models

Fig. 4 Daily abstraction from each site across the study period (red dot shows the mean value compared to the median line). Four values at Wikwatyo of >14,000 L have been removed



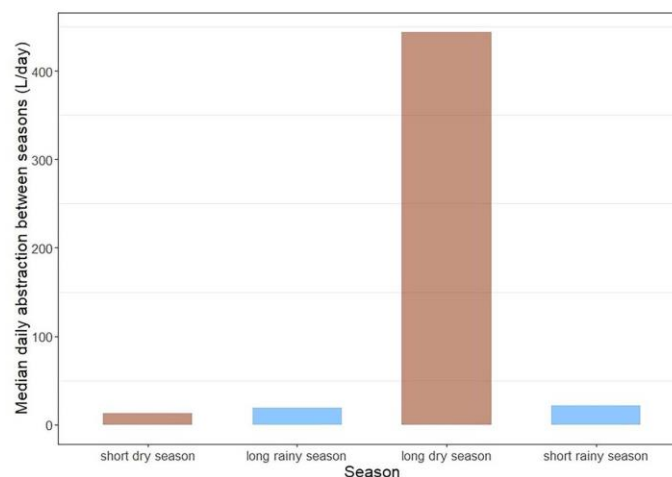
were used. Table 1 highlights the descriptive statistics of the independent variables of sand dam characteristics or individual behaviour: actual salinity, area of vertical face of dam wall, livestock use, abstraction limits, presence of rainwater harvesting tanks, distance, whether the dam is said to have ever run dry, and perceived salinity, alongside the dependent variable (median monthly abstraction per person), and the control variables month and handpump site.

Data on five of the independent variables of sand dam characteristics or individual behaviours

(Table 1): actual salinity, area of wall, livestock, abstraction limits, and RWH tank, whilst controlling for month and pump, were compared to log median monthly abstraction per person (L/day) in random effects regression model 1 (Table 2). Perceived salinity was excluded due to high collinearity with actual salinity. Ever run dry and distance were removed due to the loss of data due to 8 and 9 handpumps respectively having no values for these variables.

This first model explained 47.1% of the variation in abstraction (28.1% within and 100% between).

Fig. 5 Median daily abstraction between seasons (L/day) across all sites



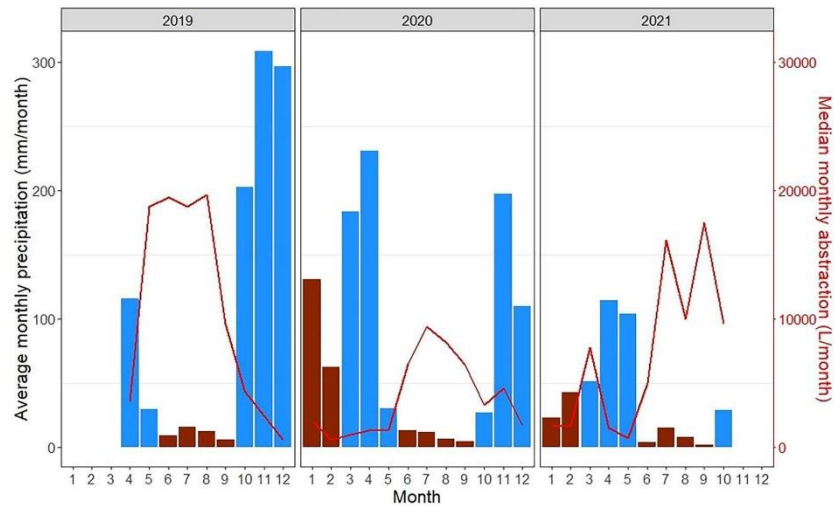


Fig. 6 Median monthly abstraction (L/month) (red line) and average monthly precipitation (mm/month) (brown bars — dry season and blue bars — rainy season) across all sites

Table 1 Selected dependent variable characteristics used in the regression models

Description	Value	Number of data points	Mean	Median	Min	Max
Dependant variable						
Median monthly abstraction per person (L/day)	0–67.5	496	5.2	1.1	0	67.5
Categorical variables						
Actual salinity (µs/cm)	0 (<1000)	254	1218	938	208	3150
	1 (1000+)	215				
Area of dam wall (m ²) — height × length of wall	0 (<90)	356	105.9	72	36.6	420
	1 (90+)	117				
Livestock usage (%) — % of interviewees using the handpumps for livestock	0 (<40)	228	40.7	33	0	100
	1 (40+)	212				
Abstraction limits (inc. only selling to members, limited number of jerry cans/p/day)	0 (no)	151	0.7	1	0	1
	1 (yes)	289				
Rainwater harvesting tank (%) — of interviewees with tanks	0 (<42)	245	43.6	40	0	83
	1 (42+)	172				
Distance (km) — average distance of round trip to handpump	0 (0.5)	185	0.7	0.5	0.5	2.1
	1 (>0.5)	166				
Ever run dry	0 (no)	275	0.1	0	0	1
	1 (yes)	44				
Perceived salinity (%) — % of interviewees perceiving water as saline	0 (<60)	161	50	50	0	100
	1 (60+)	253				
Control variables						
Month		31			04, 2019	10, 2021
Pump		26				

Table 2 Results of the regression analysis

	Model 1	Model 2
Control variables		
Actual salinity	2.489***	1.864**
Area of wall	4.132***	3.166***
Livestock use	1.252**	0.800
Abstraction limits	0.713	1.748*
RWH tank	0.788	−0.368
Distance	–	−0.955
Observations	390	284
Groups	22	16
R ²	0.471	0.500
Wald chi ²	301.44	237.88
Max VIF	1.88	2.76

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Within variation represents the total variation in the individual values in each group and their group mean whilst between variation represents the total variation between each group mean and the overall mean.

Except for September 2019, June 2020, and July 2020, 75% of the long dry months during the 3 years were found to have significantly higher abstraction than the reference month of January 2020.

Abstraction was also significantly higher in the rainy seasons of May 2019, Oct 2020, and October 2021. Sites where actual salinity was higher, dam wall area was larger, and more people were using the water for livestock had significantly higher levels of abstraction. Abstraction limits and the proportion of people with RWH tanks were not significant.

Distance was included in a second model, using the reduced number of handpumps (Table 2). Ever run dry was still excluded as its inclusion meant that the requirements for a random effects regression model were not met. The second model explained 50.0% of the variation in abstraction (27.0% within and 100% between sites). Of the long dry months across the 3 years, 41.7% significantly determined abstraction, with abstraction being significantly higher from the reference month of January 2020. Abstraction was also significantly higher in March 2021 and Oct 2021. Sites where actual salinity was higher, dam wall area was larger, and abstraction limits were in place had significantly higher levels of abstraction. Livestock use, the proportion of people with RWH tanks, and distance were not significant. As distance was not significant in model 2 and given the reduced number

of sites used, the first model is the focus of the discussion in the “Temporal abstraction trends” section.

Long dry season analysis

Of the 26 handpumps, 22 had abstraction data available for the last full week of at least one long dry season (September), with 21 having some water abstracted, indicating that they were providing water when access to other sources may have been compromised. Median daily abstraction in this week averaged across the 3 years across the 22 sites was 242L. This varied, however, between 0L at Bodeni and 5920L at Kee 13.

From the 22 handpumps for which data was available, using a household size of 3.7, 31.8% ($N=7$) of sites were classed as providing sufficient water ($>2.3\text{L/p/day}$) by the end of each long dry season (2019–2022) for which they have data available: able to meet users’ minimum drinking needs. A further 27.3% ($N=6$) met this need by the end of at least one long dry season for which they have data available. Of these 13 handpumps, 84.6% ($N=11$) were providing $>4.6\text{L}$ per person: the drinking water needs in hot climates (World Health Organisation., 2016) in at least one long dry season (indicated by an X in Table 3). These handpumps were able to meet user’s drinking water needs independently of other sources (blue in Table 3).

Of the remaining handpumps, 36.4% ($N=8$) were not providing sufficient water ($<1.7\text{L}$), failing to meet the drinking water needs of their users in any year (brown in Table 3). One handpump (Makutano) was classed as “potentially providing sufficient water” in 2020 (between 1.7 and 2.3L) (white in Table 3).

Finally, of the 21 seasons in which $>2.3\text{L}$ was being abstracted using a household size of 3.7, 81% ($N=17$) still had $>2.3\text{L}$ being abstracted when using a household size of 6.15 (indicated by a 0 in Table 3), indicating that the majority would still have been providing sufficient water to meet drinking water needs even with a larger user population.

Discussion

The contribution that sand dam handpumps make to water security is fundamental to their practicality and usefulness as a water resource in drylands. It was

Table 3 The handpumps and years where minimum user drinking needs are and are not being met by the last full week of the long dry season (September) based on median weekly abstraction (L/p/day) using an average household size of 3.7 (dark blue = >2.3L/p = providing sufficient water, brown =

<1.7L/p = not providing sufficient water, white = potentially providing sufficient water (1.7–2.3L/p), grey = missing data, X = providing >4.6L/p, 0 = providing >2.3L/p when using a household size of 6.15)

	Site	No. of households	2019	2020	2021
1	Athiani	18			
2	Bodeni	9			
3	Ikanga	12	X 0		
4	Katelembu 16	30	X 0		
5	Katelembu 17	30			
6	Kee 13	100	X 0		
7	Kee 14	60			
8	Kinuvu	46			
9	Kinyenyoni	47			
10	Kithangaini 17	73			
11	Kithangaini 18	97			
12	Kithunthi	98	X 0	X 0	0
13	Makutano	20			
14	Mapatano 17	12	X 0	X 0	X 0
15	Mapatano 18	19			
16	Mbukilye	27			
17	Mukaso	86			
18	Mutula	26	X 0		X 0
19	Ndwae	43		X 0	X 0
20	Sindano	31			
21	Syakama 16	51			
22	Syakama 18	62			X 0
23	Wendo	29		X 0	
24	Wikwatyo	21	X 0		
25	Woni 15	55			
26	Woni 16	72			X 0

hypothesised that sand dams improve communities' year-round water security by providing water from handpumps in the dry season. As the first to analyse a long-term timeseries of abstraction data from sand dams, this study supports this hypothesis in general; however, heterogeneity between sites and missing data do not make general conclusions possible.

Temporal abstraction trends

Abstraction from the handpumps is highly heterogeneous between seasons. When rainfall is higher, utilisation of handpumps is generally lower. This is consistent with the findings of Thomson et al. (2019) who studied the relationship between rainfall and groundwater use in Kwale County on Kenya's southern coast. They found highest weekly abstraction (average 2335L/pump/day) to be the first week of March, at the end of the short dry season. This was three times greater than that of the second week of May (average of 789L/pump/day), around the peak of the rains. This is consistent with the regression model in this study which found significantly higher abstraction in 75% of the long dry season months. It is possible that the lack of significance in the two months in 2020 was because of a wetter than average long rainy season, meaning that other surface water sources were more readily available.

Lower levels of abstraction observed in months outside of the dry season are hypothesised to be linked to the recorded increase in use of multiple sources in the rainy season (Arouna & Dabbert, 2010; Elliott et al., 2017; Kelly et al., 2018). Despite the assumed availability of water in the sand dams in the rainy season, people may choose to use other sources for numerous reasons such as cost, labour, and convenience, the latter of which is often cited as the most influential (Dessalegn et al., 2013). Many sources, however, are compromised in the dry season, forcing use of alternative sources (Chan, 2019; Kaptué et al., 2013; Kelly et al., 2018; van Houweling, 2016), likely explaining why sand dam handpump abstraction increases.

This study found a 34-times increase in median daily abstraction between seasons (L/day) from the sand dam handpumps from the short dry to the long dry season. Neufeld et al. (2020) found abstraction from sand dams in the Ukambani region of Kenya to increase from around 50 to 70% of households from

the rainy to dry season, whilst RWH tank usage fell from >80 to just 10%. Thomson et al. (2019) similarly found that 86% of households used handpumps as their main drinking water source in the dry season compared to 6% in the rainy season, whilst participants interviewed for this study reported to fetching less or no water from handpumps when their rain-water harvesting tanks are full. Understanding the response of sand dams to rainfall highlights their resilience to future changes in climate and their applicability in drought-prone areas (Macdonald et al., 2019). By providing insight into when abstraction is lower, this study can help to inform water providers on times of the year when water supply from other sources such as vendors may need expanding.

Heterogeneity in abstraction

The results show high heterogeneity in abstraction between handpumps, with median daily abstraction ranging from 2 to 2962L. Possible reasons for this heterogeneity include water availability due to sand dam characteristics, including area of wall, grain sizes, depth of sediment, width of riverbed, and slope of banks (Aerts et al., 2007; Borst & de Haas, 2006; de Trinchiera et al., 2015; Jansen, 2007; Nissen-Petersen, 2006; Quinn et al., 2019; Strohschein, 2016) and environmental characteristics, including rainfall, soil, geology, accessibility, topography, and stream order (Jeil et al., 2020; Ngugi et al., 2020; Thwala, 2010; Wrisdale et al., 2017; van Houweling, 2016). Additionally, social factors including number of users, average distance to each dam, quality, safety, availability and use of other sources, perceptions, volume abstraction limits, tradition, price, and water use practices (particularly whether livestock drink directly from pooled water or if water is fetched for them from the handpump) may impact use (Chan, 2019; Devoto et al., 2012; Elliott et al., 2017; Howard, 2002; Jiang & Rohendi, 2018; Parameswari et al., 2016; WHO & UNICEF, 2017).

Modelling of sand dam characteristics against abstraction volume goes some way to explaining the variation seen across sites. In the regression model, abstraction was significantly higher at sites with higher actual salinity, larger dam walls, and where a greater proportion of interviewees use the water for livestock.

Actual salinity

Abstraction was significantly higher at sites with higher salinity ($>1000 \mu\text{S/cm}$). The WHO (2017) permissible level of electrical conductivity for drinking water is $2500 \mu\text{S/cm}$, of which 12% ($N=3$) of samples exceeded. People often seek alternative sources to using saline water for drinking (Kinniburgh & Smedley, 2001) due to perceived health implications, such as hypertension, (pre)eclampsia and infant mortality (in pregnant women), respiratory infection, and kidney disease (al Nahian et al., 2018; Rutherford et al., 2015; Shammii et al., 2019). As only a small part of daily water use is used for drinking, it was discovered that abstraction was higher at locations used to meet other needs, with individuals continuing to use saline water for purposes other than drinking. Despite measured salinity being higher at Woni 16, this handpump was used more than Woni 15, with people continuing to use Woni 16 for livestock and domestic use, compared to Woni 15, which was used for cooking and drinking.

Dam wall area

At 52% of sites, the dam wall has an area of 90m^2 and above (Table 1), at which abstraction was significantly higher. This is likely due to a greater volume of sand being able to build up behind a larger dam wall, and therefore a greater volume of water being stored (Borst & de Haas, 2006; Jansen, 2007; Maddrell & Neal, 2012; van Loon & Droogers, 2006).

Livestock

At 45.8% of sites, $>40\%$ of interviewees were using the handpump water for livestock (Table 1). These sites experienced significantly higher abstraction. When comparing interviewees' self-reported abstraction volumes to livestock usage, it was found that those using the pumps for livestock were abstracting 30.6% more water. It is estimated that a minimum of 7.5L/p/day is required to meet basic domestic water needs (Howard & Bartram, 2003), compared to higher requirements for livestock, with growing heifers of 182 kg in 32.2°C having an approximate daily water intake of 36 L (Subcommittee on Beef Cattle Nutrition et al., 2000).

Variables that do not predict abstraction volume

Abstraction limits did not significantly predict abstraction in the model, suggesting their lack of impact on water use. Sand dam users on the ground can assess the availability of water from the dams to a much better extent than a model can do and should and will continue to do what they consider necessary to conserve and sustain water resources.

Finally, the lack of significant impact of RWH tanks on abstraction suggests people's reliance on the handpumps independently of RWH tanks. This is likely because RWH tanks are used to a greater extent in the rainy season (Adekalu et al., 2002; Boelee et al., 2013; Elliott et al., 2017; Özdemir et al., 2011; Shaheed et al., 2014), compared to sand dam handpumps which are used more in the dry season, indicating that a holistic view of rainwater harvesting needs to be taken, considering all available options as one managed whole.

Drinking water needs

Of the 22 handpumps with available data, 21 had some water abstracted by the last week of the long dry season (median daily abstraction of 242L), indicating a contribution to year-round water security. This is consistent with Hanson and Nilsson (1986) who cite that in Bombas, Ethiopia, "the dam is full several months after the end of the rainy season" and Quillis et al. (2009) who claim that "sand-storage dams can effectively increase water availability throughout the dry season". Whilst this is true, the level to which they can meet water needs independently of other sources is questionable at some sites due to high heterogeneity in handpump abstraction.

The results from Table 3 clearly demonstrate that the level of abstraction is not sufficient to support the drinking needs of all users of all handpumps in all years. This heterogeneity is consistent with the findings of Ngugi et al. (2020), who used a water requirement calculation using number of households, persons per household, daily per capita water requirements, and number of days in the long dry season, followed by a survey to assess whether dams were meeting these needs. They found that only 42% of dams could meet household water demand throughout the whole long dry season, whilst our study found that 59.1% were meeting drinking water needs by the end of at least one long dry season.

The variation in abstraction between years shows that whilst some handpumps can provide 2L/person/day, other factors may be impacting abstraction such as the availability of other sources, population numbers which may not remain stable, variable rainfall rates, and the maturity of the dam. The lack of data for some sites also means that further conclusions cannot be drawn.

Whilst sites were selected due to a known reasonable signal, across the period that each transmitter was live there is some missing data. Uneven proportions of missing data in different seasons and sites place limitations on the comparisons that can be made between sites and time periods. This is an inherent challenge in certain, especially rural settings across the world. This study in part overcame this uncertainty by using average values and developing exclusion criteria. It can also be argued that the benefits of using WDT over or in coordination with traditional methods of data collection outweigh the uncertainties. Using this data, the study has positively contributed to the literature on sand dams. Whilst there is heterogeneity in abstraction between seasons and sites, many handpumps are still being used by the end of the long dry season, with significantly more abstraction seen at sites with higher salinity, larger dam walls, and higher livestock usage. Sand dams can therefore be seen as an effective dryland water source, especially useful in the dry season.

Conclusion

As the first study to analyse multi-year abstraction trends from sand dam handpumps, it reveals, quantitatively, the positive contribution that sand dams can make to year-round water security, by providing a water source by the end of the long dry season when other water sources are compromised. Of 22 handpumps with abstracted data for the end of at least one long dry season, 59.1% suggest they can meet drinking water needs by the end of the long dry season independently of other sources.

Having said this, heterogeneity in abstraction is a reminder that not all sand dams behave the same, with certain sand dams always likely to have higher levels of abstraction than others, such as those with higher user numbers, levels of salinity, livestock use, and larger dam walls. The findings of low abstraction from certain handpumps and in certain months challenge sweeping

statements in literature professing the success and perfection of all sand dams, which are neither accurate nor helpful. Yet, as abstraction levels are not synonymous with water storage in the dam, with many confounding factors impacting level of abstraction, without further research, their true capabilities are unknown. High abstraction and sustained water availability by the end of the long dry season at many sites profess the positive contribution that sand dams can make to a community's water supply, offering opportunities for further success in the future.

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Positionality statement I include this positionality statement as a declaration of my current understanding of who I am and how this may impact my work. I include it to be transparent about my identity and background so that you, as the reader, can know the perspective of the author. I am a British, white, female, early career researcher. Whilst my research is based in Kenya, I had never visited Kenya until 2022. My research is quantitative and includes no people as research subjects. However, my personal and social identities culminated in the privileged position that has allowed me to conduct this research in the first place and may have biased the research that I have undertaken.

Author contribution Software, formal analysis, investigation, data curation, writing — original draft, and visualisation were performed by Hannah Ritchie. Conceptualisation was performed by Hannah Ritchie and Alison Parker. Methodology was performed by Hannah Ritchie, Ian Holman, and Alison Parker. Supervision was performed by Ian Holman and Alison Parker. Writing — reviewing and editing was performed by Ian Holman, Alison Parker, and Joanna Chan.

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Data availability The data sets analysed during the current study are available in the Cranfield University repository (CORD) at <https://doi.org/10.17862/cranfield.rd.21435690>.

Declarations

Competing interests The authors declare no competing interests.

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Appendix C: Published paper: Sand dam contributions to year-round water security

monitored through telemetered handpump data in Environmental Monitoring and Assessment

Appendix D Community survey on handpump use

1. What is your main source of water? And what is the purpose of use?
2. Do you have access to the handpump? (i.e. is the handpump locked? Do you have the keys to access?)
3. Do you have to pay to use the handpump from the sand dam?
4. How far (distance) and how long does it take to walk to your closest handpump/water source?
5. How many times a day do you travel to collect water from the water source, what time of day, and by what means? (i.e. bucket, trolley, etc.)
6. Are there volume abstraction limitations from wells per household set by the organization/owner of the sand dams?
7. Have you ever experienced the handpump running dry? (not enough water?)
8. What does the water from the handpumps taste like versus scoop holes (if using)?
9. Are there any suspected illnesses after using handpumps/scoop holes/other water sources relating to the sand dams? Do you treat the water?
10. Are there any water vendors in the area abstracting water from the sand dams?
11. Rainwater Harvesting tanks?

Other Comments:

Appendix D: Community survey undertaken by Chan (2019) on sand dam handpumps and other water sources

Appendix E Variable values used in random effects models

Pump	Daily litres range (L)	Daily rainfall range (mm)	Actual salinity ($\mu\text{S}/\text{cm}$)	Area of wall (m^2)	Livestock use (%)	Abs limits	RWH tank (%)	Distance (km)	Perceived salinity (%)	Ever run dry
Athiani	0-5348	0-66.145	2700		12.5	No			0.625	No
Bodeni	0-3863	0-63.394	545	79.04	50	Yes	18	0.8	0	Yes
Ikanga	0-1701	0-122.825	405	249.76	0	No	75		1	No
Katelembu 16	0-3664	0-94.799	1155	156.24	0	No	33	0.5	0.666	No
Katelembu 17	0-2597	0-28.362	1076	171.6	15	No	22	0.5	0.7	No
Kee 13	0-10317	0-110.883	208	54.5	40	Yes	17	0.6	0	
Kee 14	0-5487	0-110.883	902	209.05	33	No	17	0.6	0	
Kinuvu	0-9272	0-122.550	877	61.18	40	Yes	0	0.5	1	No
Kinyenyoni	0-2964	0-77.504	743	146.74	0	Yes	40		0	No
Kithangaini 17	0-2820	0-117.058	1740	128.04	0	No	50		0	
Kithangaini 18	0-6271	0-102.368	391	420	0	No	50		0.333	
Kithunthi	0-5492	0-126.019	1353	80.64	33	Yes	67	0.5	0.888	No
Makutano	0-5987	0-67.276		65	75	Yes	38	0.5	0.071	Yes
Mapatano 17	0-7767	0-121.394	614	63.546						
Mapatano 18	0-3149	0-121.394	938	96.725						
Mbukilye	0-2787	0-101.864	575	97.23	33	Yes	25	0.5	0	No
Mukaso	0-3565	0-110.883	872	66.36	60	No	40		0.5	No
Mutula	0-3871	0-87.971	1985	268.38	86	Yes	43	0.8	0.857	No
Ndwae	0-5466	0-119.905	1098	71.051	100	No	40	0.5	1	
Sindano	0-3203	0-101.864	855	64.842	0	Yes	83	0.9	0	No
Syakama 16	0-3136	0-60.886	1090	93.84	62.5	Yes	63	0.6	0.5	Yes
Syakama 18	0-10906	0-60.886	1162	36.625	50	Yes	50	0.6	0.5	No
Wendo	0-4740	0-117.058	3150	43.51	0	Yes	33		1	
Wikwatyo	0-20505	0-76.852	2690	72	100	Yes	20	2.1	1	No
Woni 15	0-7833	0-64.835	427	139.95	0	Yes	46	0.5	0	No
Woni 16	1-12473	0-61.038	1294	102.6	100	Yes	46	0.5	1	No

Appendix E: Raw variable values collected for each sand dam site used in the random effects models

Appendix F ERT profile locations

	Downstream (1)	Just upstream (2)	Far upstream (3)	Perpendicular (4)
Kithunthi	45m; 160m long	20m; 160m long	120m; 160m long	200m long crossing wall
Kipico	16m; 160m long	9m; 160m long	135m; 160m long	200m long crossing wall
Ngulai	13.5m; 160m long	9m; 160m long	150m; 160m long	200m long crossing wall
Nthonzweni	20m; 200m long	5m; 200m long	95m; 200m long	200m long crossing wall
Wambiti	15m; 200m long	10m; 200m long	110m; 200m long	200m long crossing wall
Kyakivandi	65m; 200m long	45m; 160m long	140m; 160m long	160m long upstream 160 long downstream

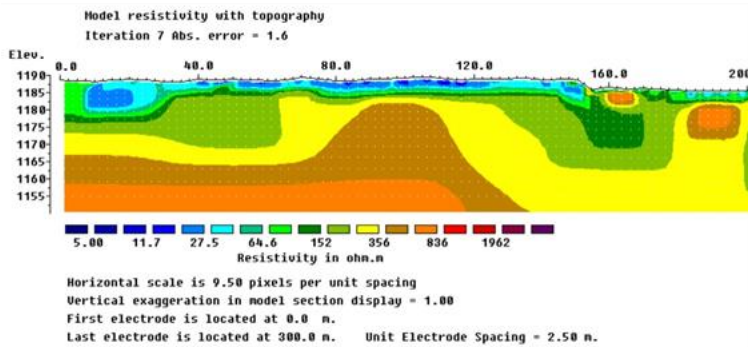
Appendix F: Inventory of the location of the ERT profiles relative to the sand dam wall and length of profiles 1-4 at each site. All profiles were undertaken in 2022. Profiles at Kithunthi, Nthonzweni, Wambiti, and Kyakivandi were repeated in 2023.

Appendix G Geophysics profiles

Key

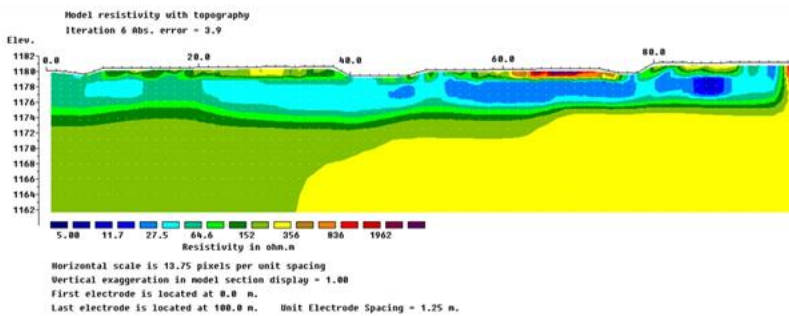
FUS	Far upstream (profile 3)
JUS	Just upstream (profile 2)
DS	Downstream (profile 1)
FFUS	Further upstream (profile 5)
E1=FUS	For perpendicular profiles, the 1 st electrode in profile on the left hand side of the profile is positioned far upstream of the dam wall, and the final electrode on the right hand side of the profile is positioned either downstream or just upstream of the dam wall
E1=RHS	For parallel profiles, the 1 st electrode in profile on the left hand side of the profile is located on the right hand side of the riverbed when looking upstream
Perpendicular RHS	A profile perpendicular to the dam wall following the right hand side riverbank at the edge of the riverbed
Res	Resistivity profile
IP	Induced Polarisation profile

Kithunthi



Perpendicular. E1 = FUS

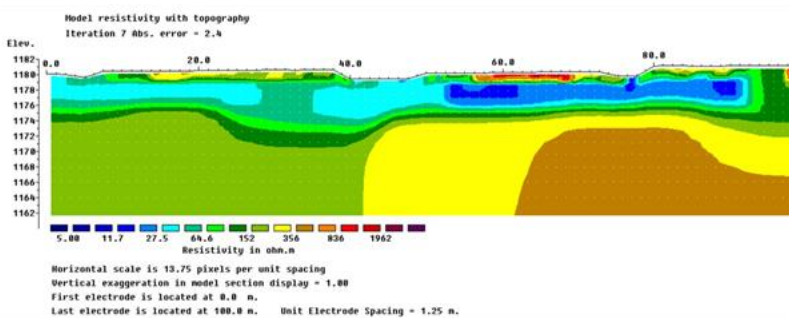
Gradient res 2022



Perpendicular RHS. E1 =

FUS

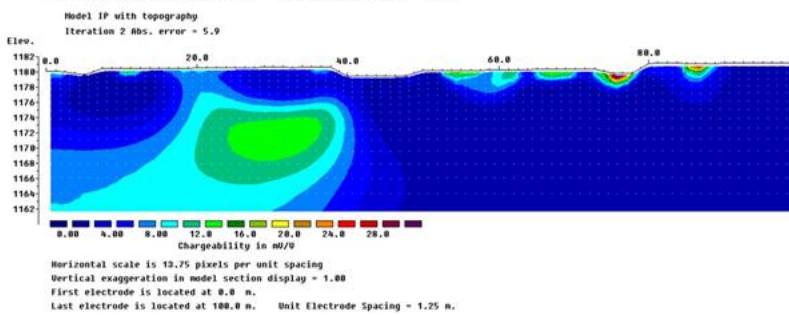
Gradient res 2023



Perpendicular RHS. E1 =

FUS

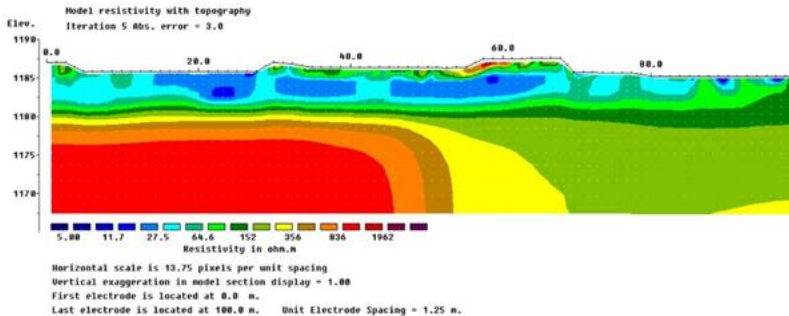
Schlumberger res 2023



Perpendicular RHS. E1 =

FUS

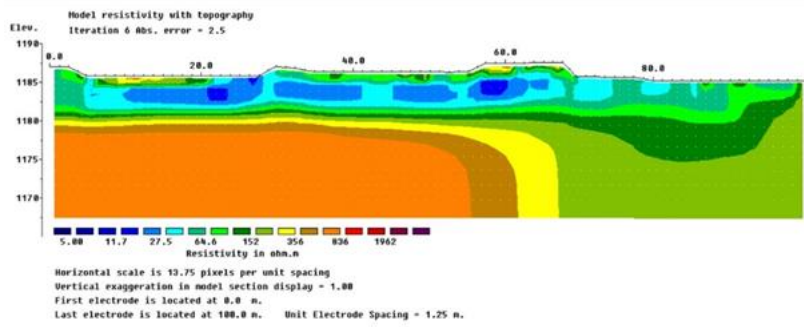
Schlumberger IP 2023



Perpendicular LHS. E1 =

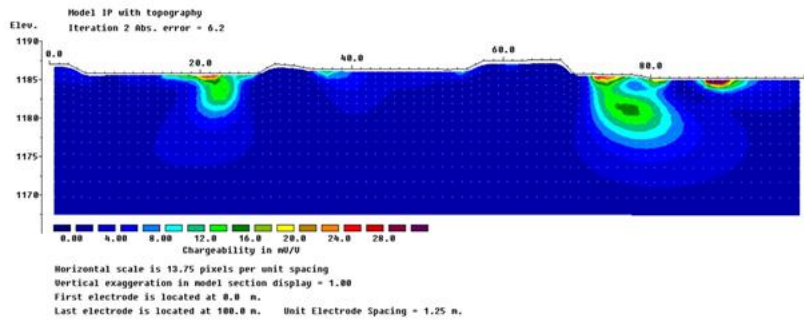
FUS

Gradient res 2023



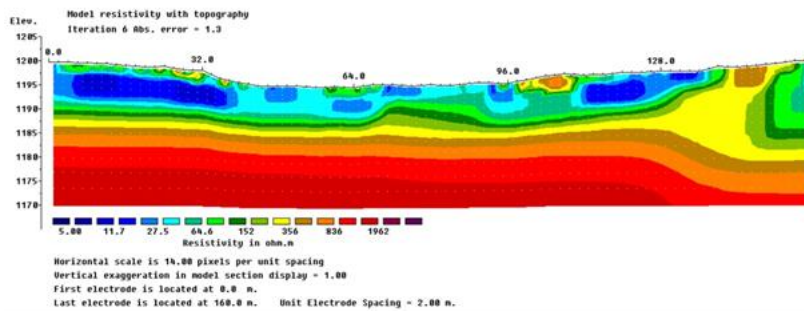
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FUS

Schlumberger res 2023



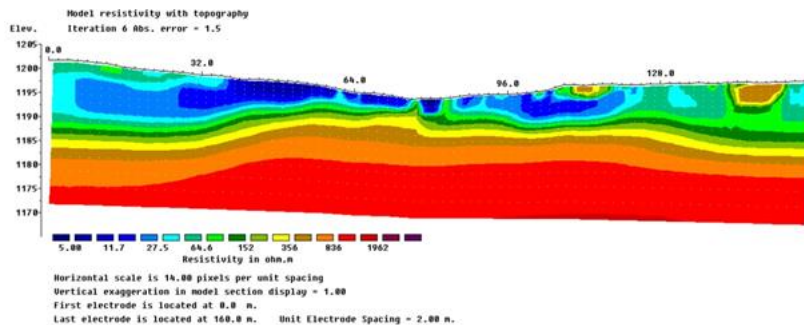
Perpendicular LHS. E1 =
FUS

Schlumberger IP 2023



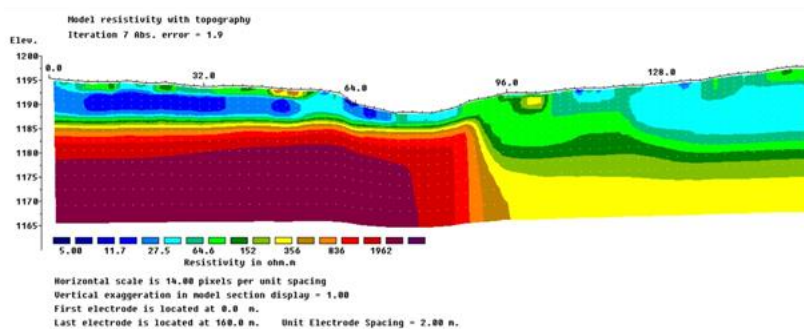
JUS. E1 = RHS

Gradient res 2022



FUS. E1 = RHS

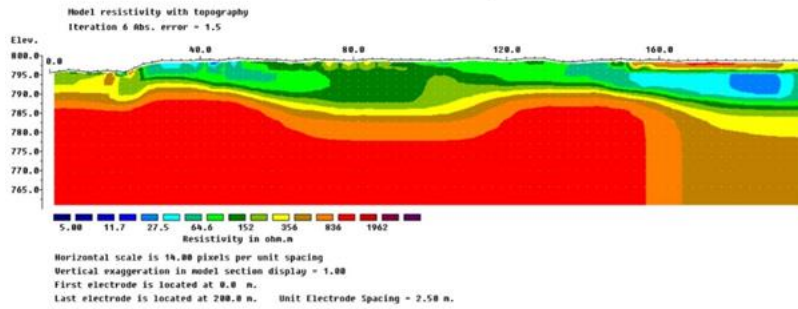
Gradient res 2022



DS. E1 = RHS

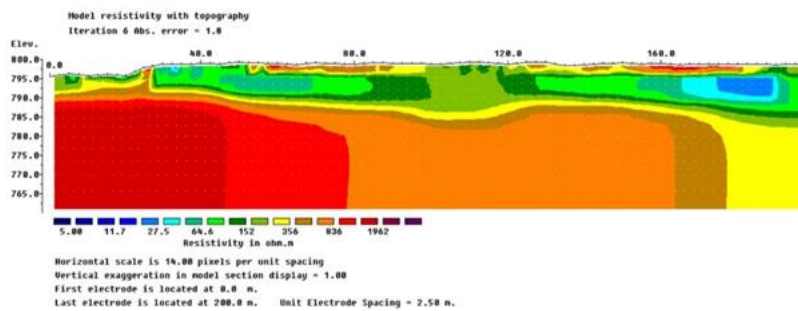
Gradient 2022

Kipico



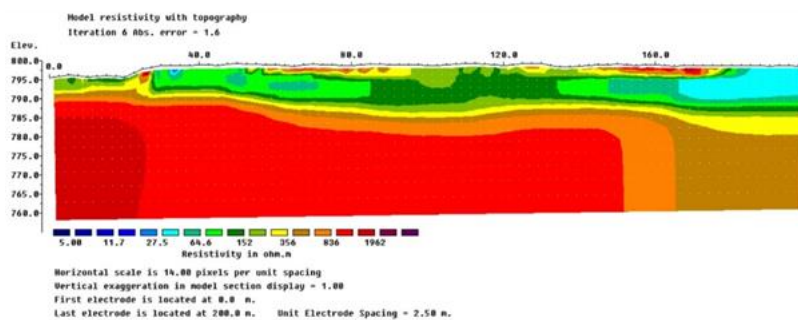
Perpendicular. E1 = DS

Gradient res 2022



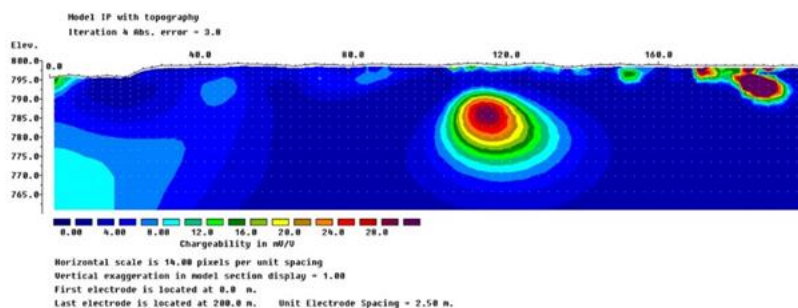
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Gradient res 2023



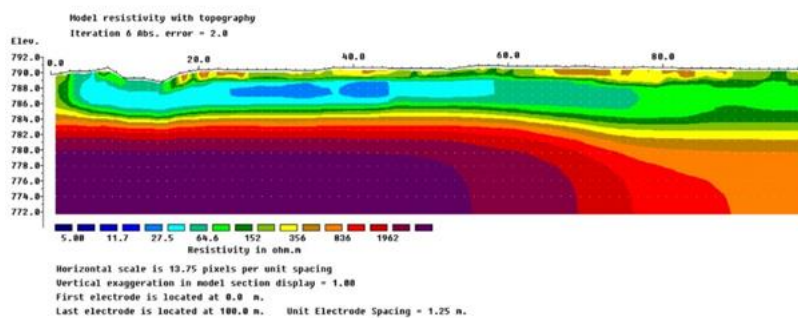
Perpendicular. E1 = DS

Schlumberger res 2023



Perpendicular. E1 = DS

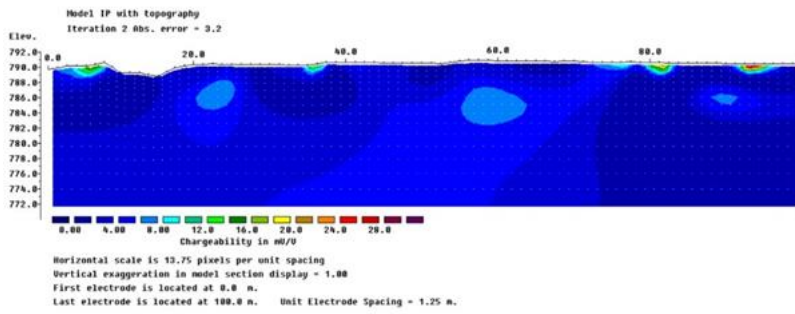
Schlumberger res 2023



Perpendicular LHS. E1 =

JUS

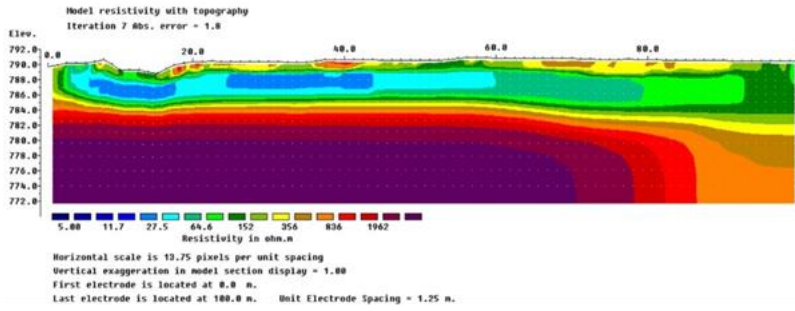
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Perpendicular LHS. E1 =

JUS

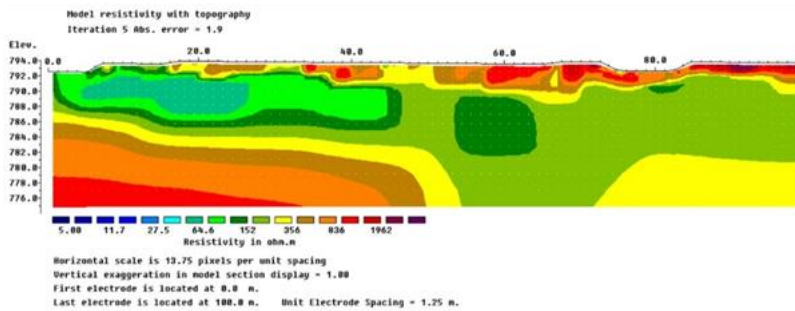
Gradient IP 2023



Perpendicular LHS. E1 =

JUS

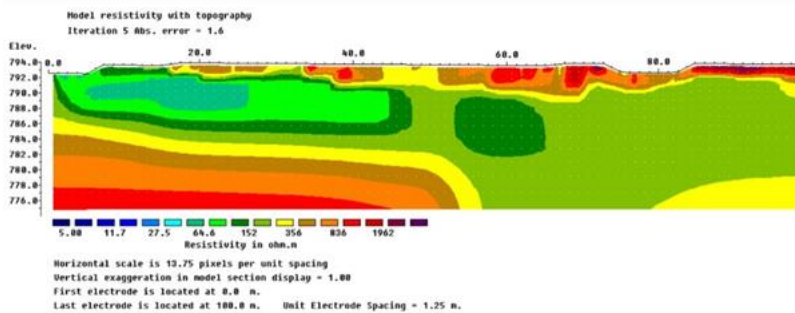
Schlumberger res 2023



Perpendicular RHS. E1 =

JUS

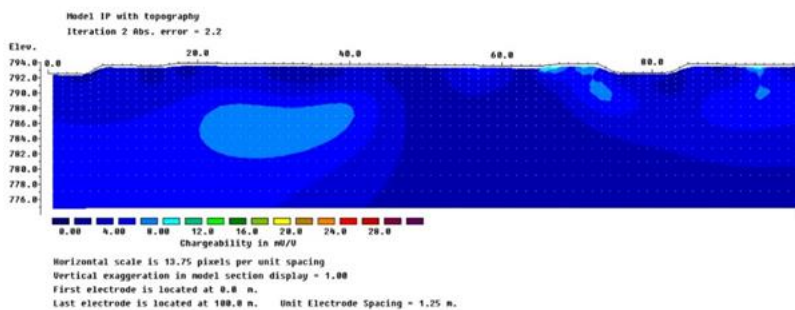
Gradient res 2023



Perpendicular RHS. E1 =

JUS

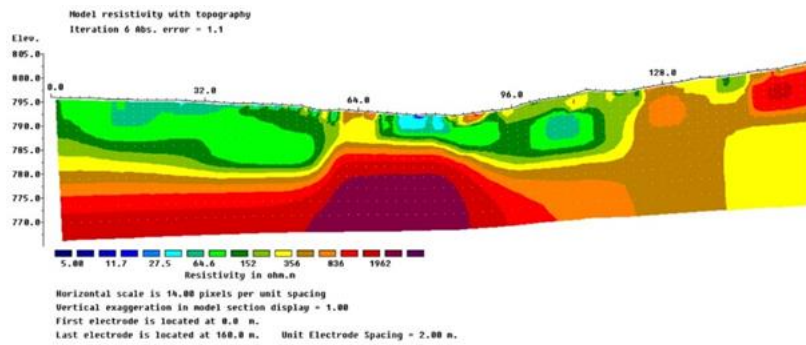
Schlumberger res 2023



Perpendicular RHS. E1 =

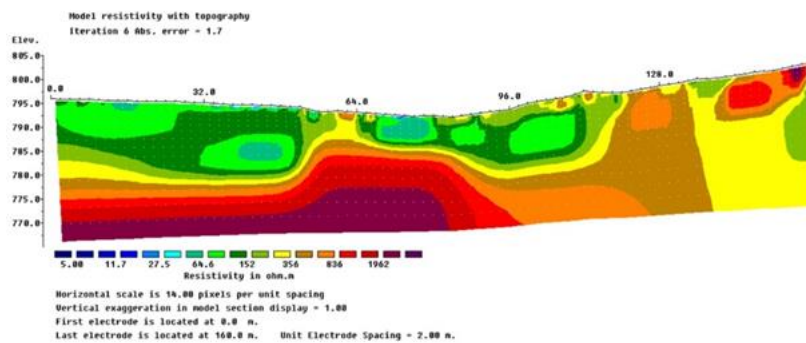
JUS

Schlumberger IP 2023



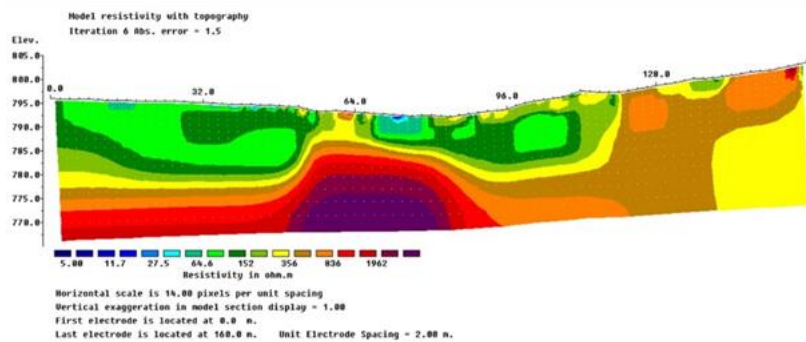
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Gradient res 2022



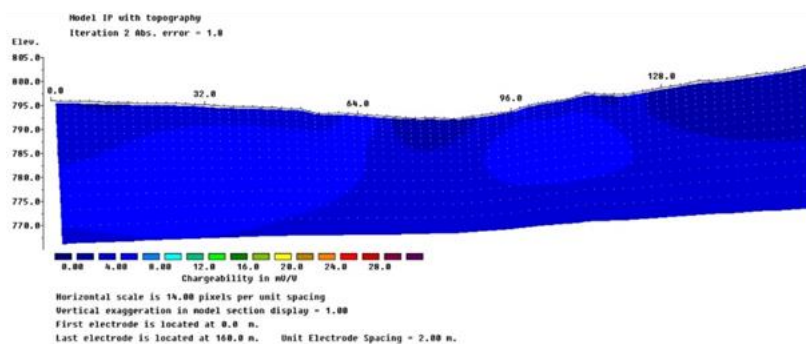
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Gradient res 2023



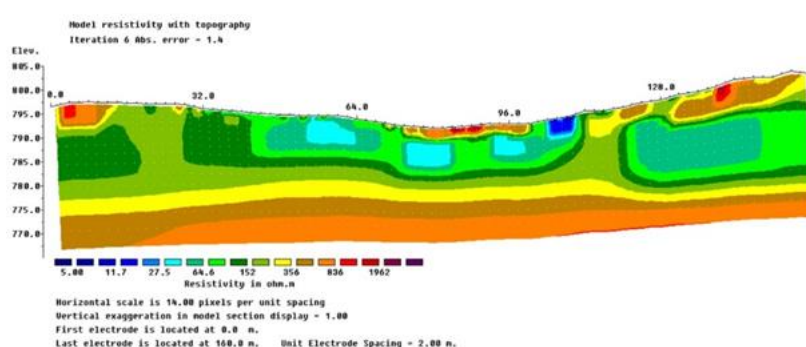
JUS. E1 = LHS

Schlumberger res 2023



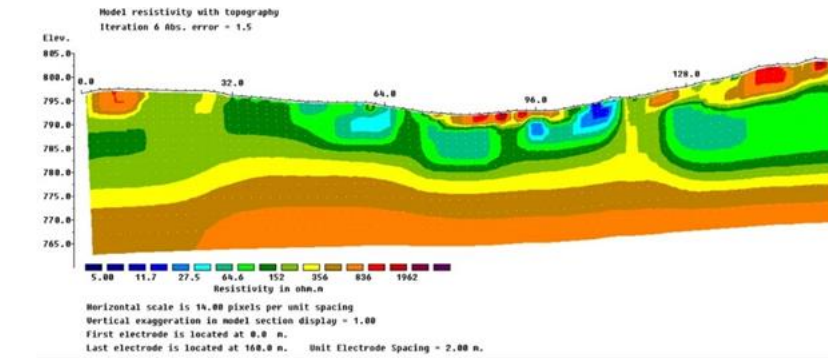
JUS. E1 = LHS

Schlumberger IP 2023



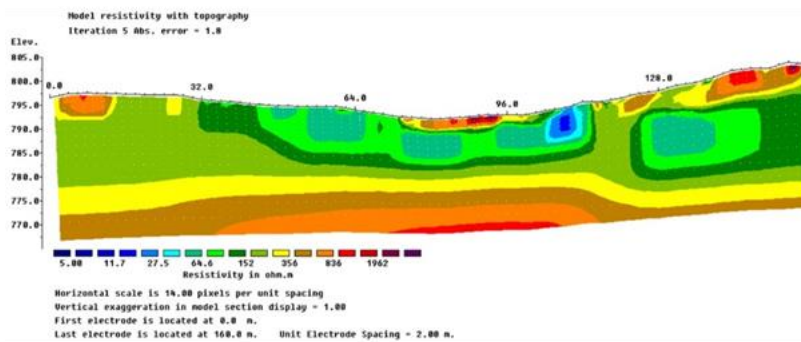
FUS. E1 = LHS

Gradient res 2022



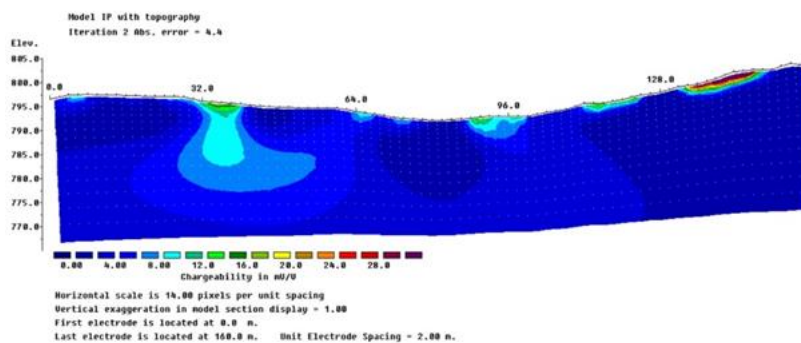
FUS. E1 = LHS

Gradient res 2023



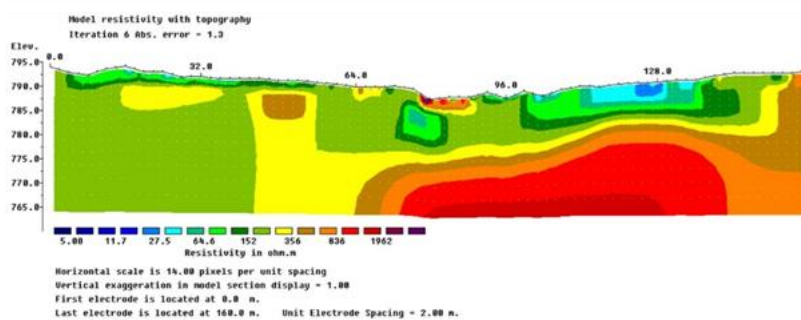
FUS. E1 = LHS

Schlumberger res 2023



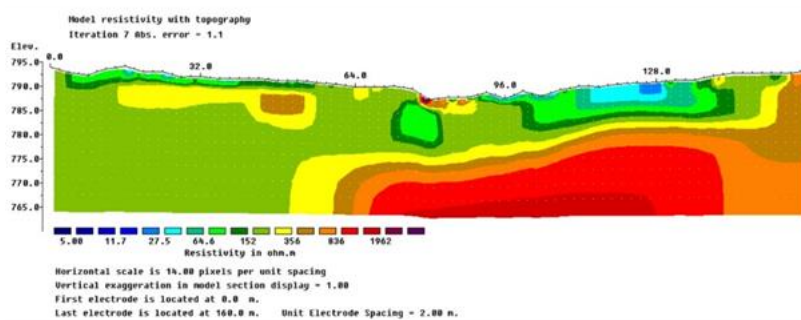
FUS. E1 = LHS

Schlumberger IP 2023



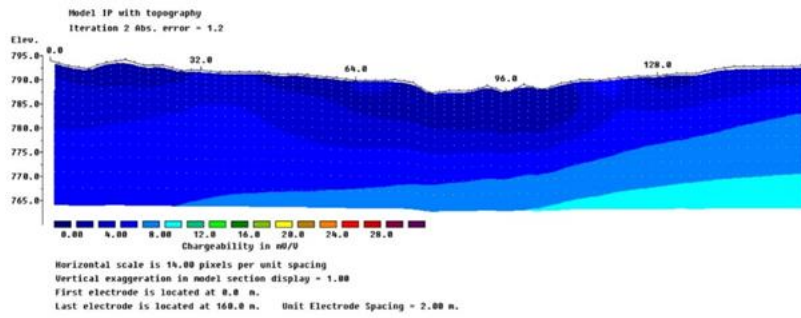
FFUS. E1 = LHS

Gradient res 2023



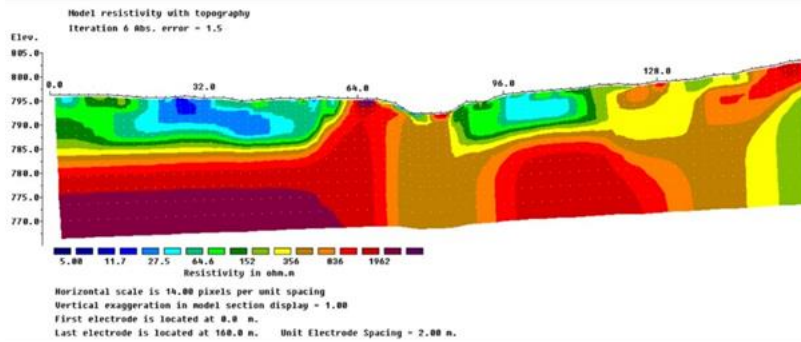
FFUS. E1 = LHS

Schlumberger res 2023



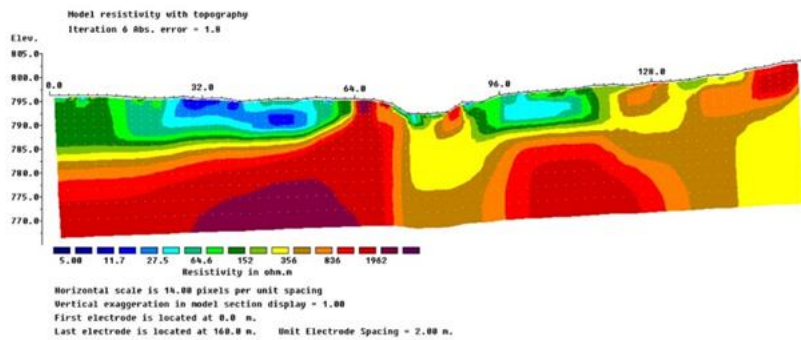
FFUS. E1 = LHS

Schlumberger IP 2023



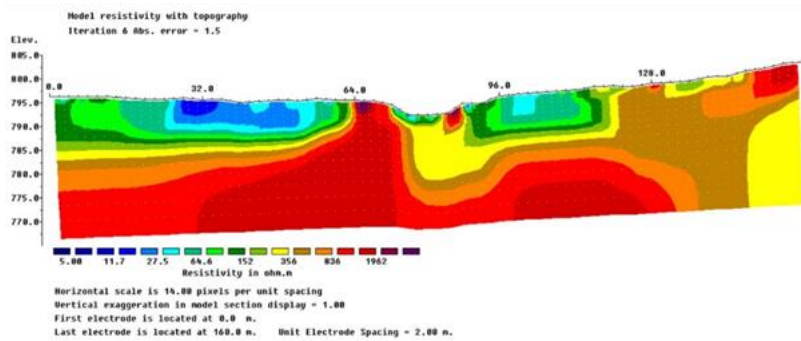
DS. E1 = LHS

Gradient res 2022



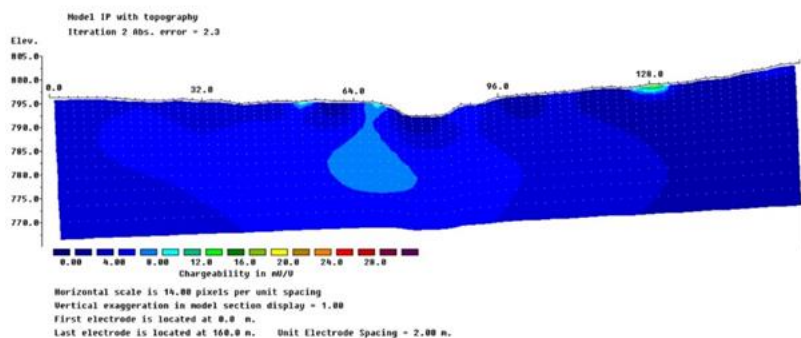
DS. E1 = LHS

Gradient res 2023



DS. E1 = LHS

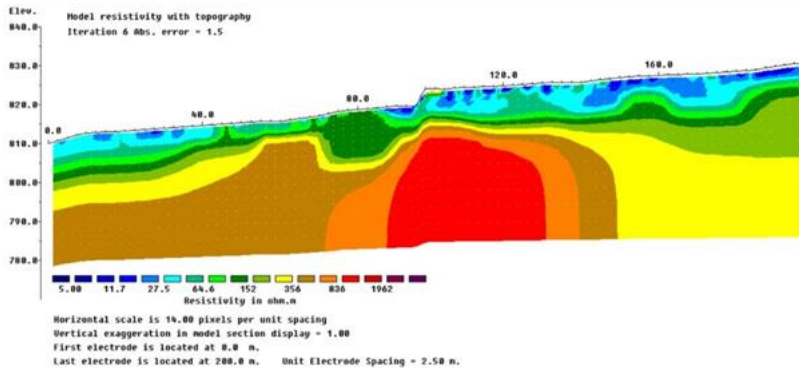
Schlumberger res 2023



DS. E1 = LHS

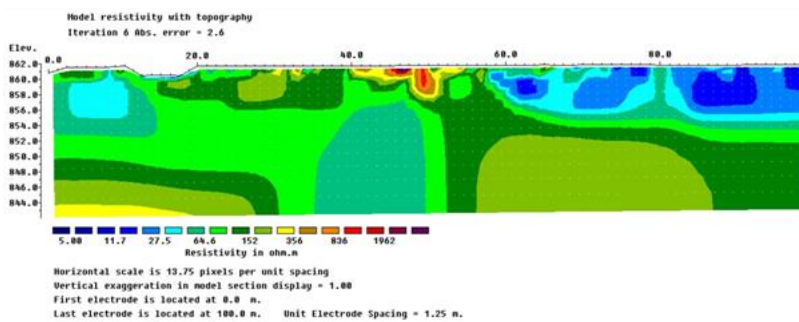
Schlumberger IP 2023

Ngulai



Perpendicular. E1 = DS

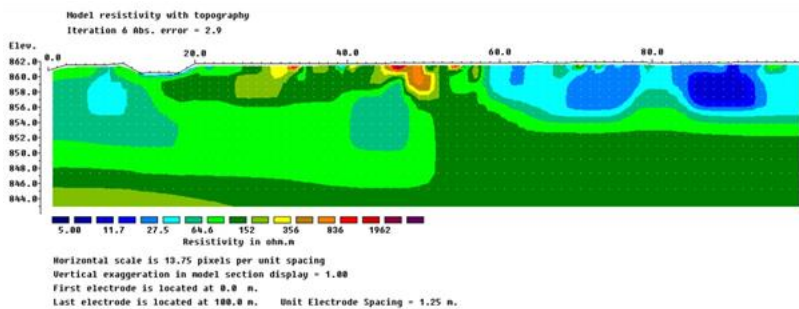
Gradient res 2022



Perpendicular RHS. E1 =

JUS

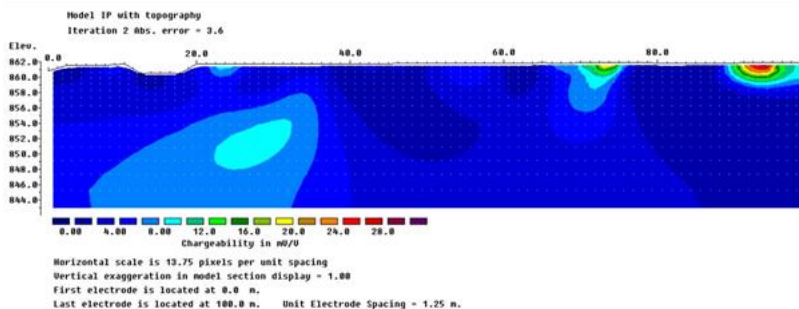
Gradient res 2023



Perpendicular RHS. E1 =

JUS

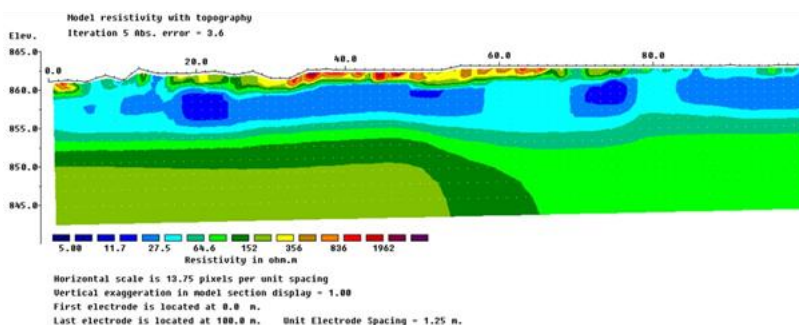
Schlumberger res 2023



Perpendicular RHS. E1 =

JUS

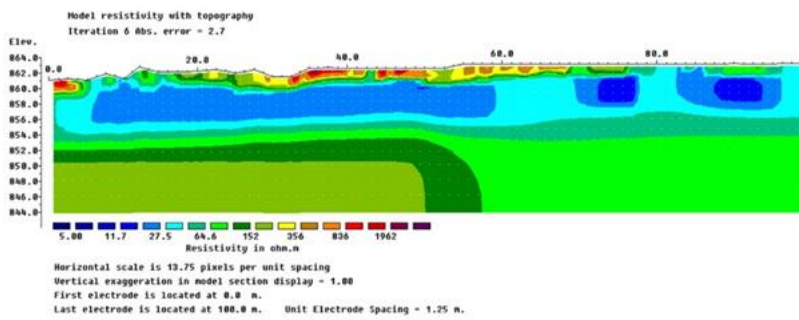
Schlumberger IP 2023



Perpendicular LHS. E1 =

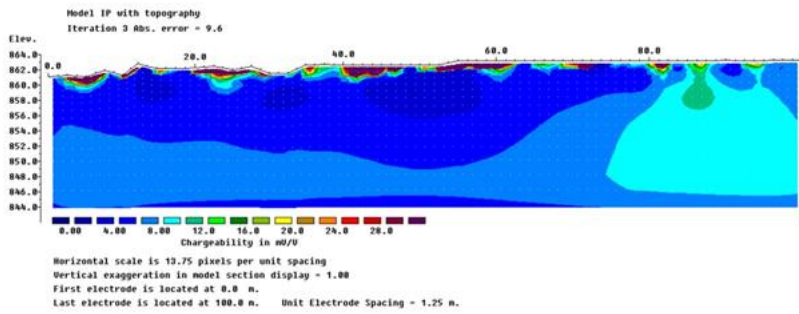
JUS

Gradient res 2023



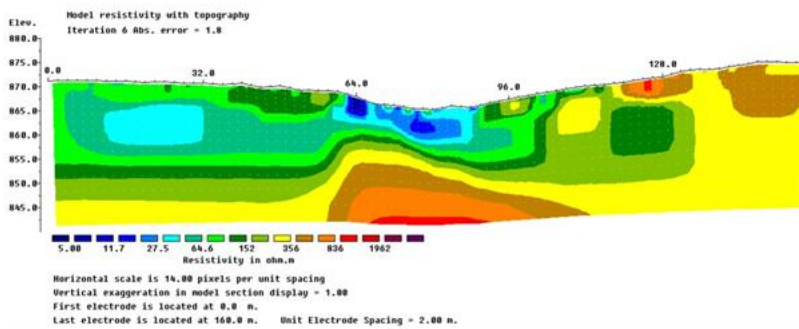
Perpendicular LHS. E1 =
JUS

Schlumberger res 2023



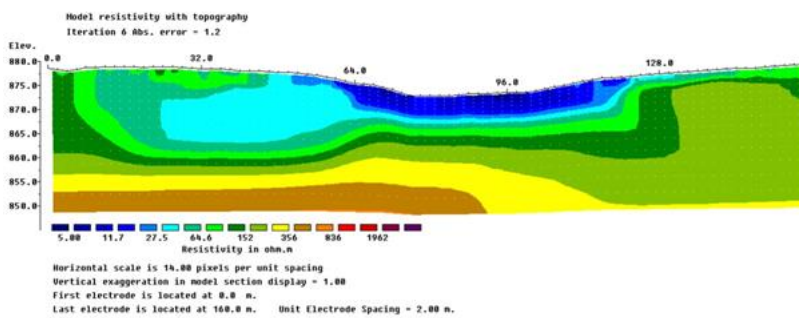
Perpendicular LHS. E1 =
JUS

Schlumberger IP 2023



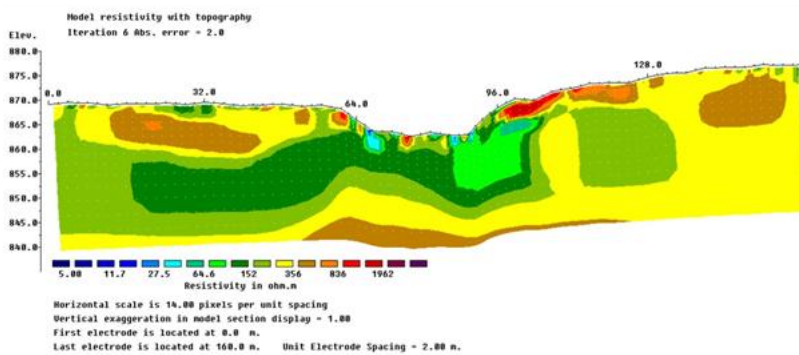
JUS. E1 = LHS

Gradient res 2022



FUS. E1 = LHS

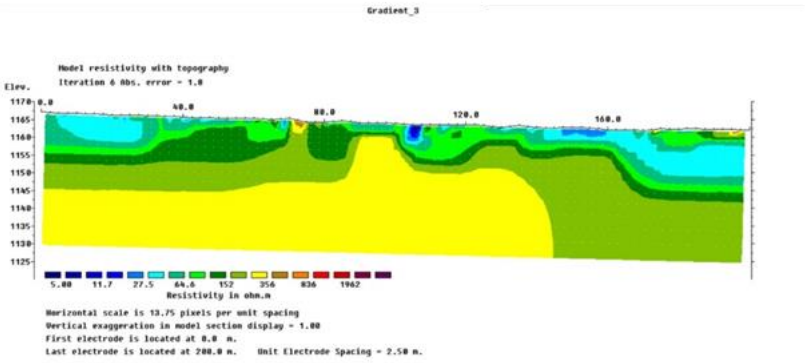
Gradient res 2022



DS. E1 = LHS

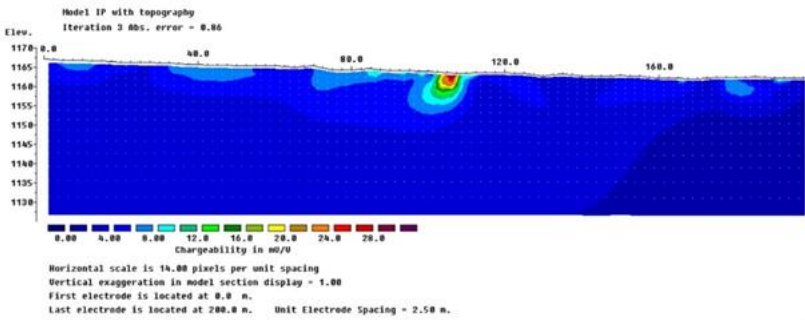
Gradient res 2022

Nthonzweni



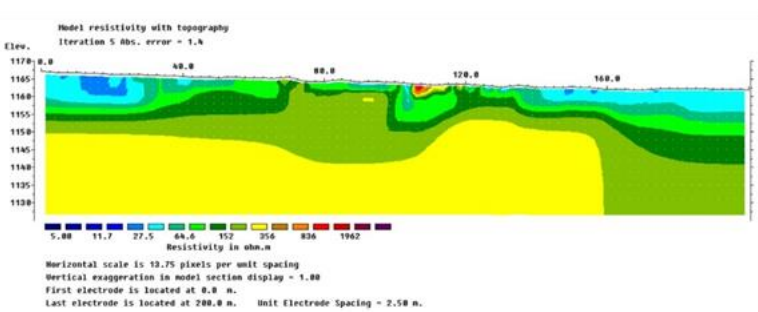
Perpendicular. E1 = US

Gradient res 2022



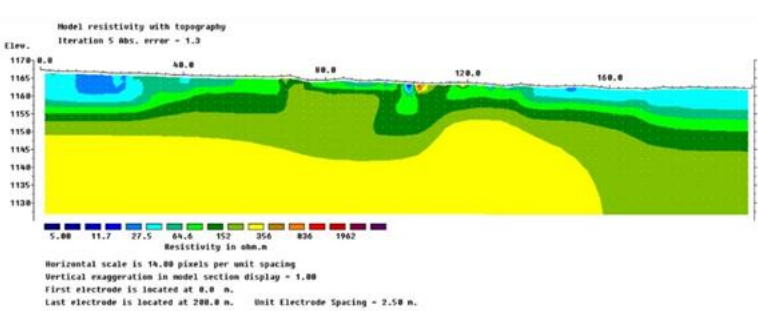
Perpendicular. E1 = US

Gradient IP 2022



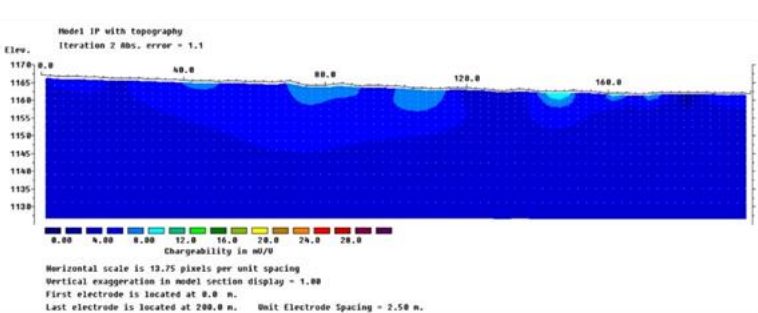
Perpendicular. E1 = US

Gradient res 2023



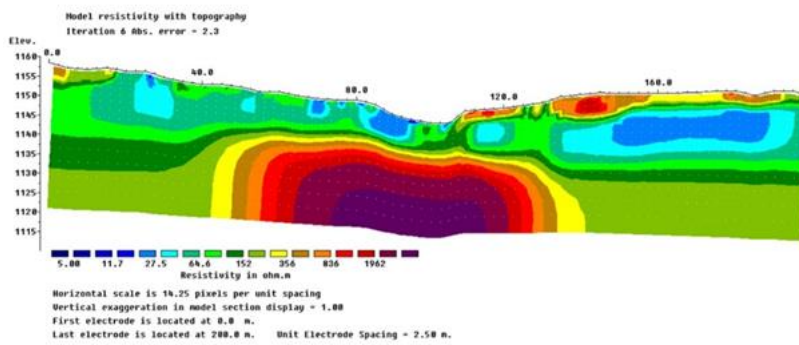
Perpendicular. E1 = US

Schlumberger res 2023



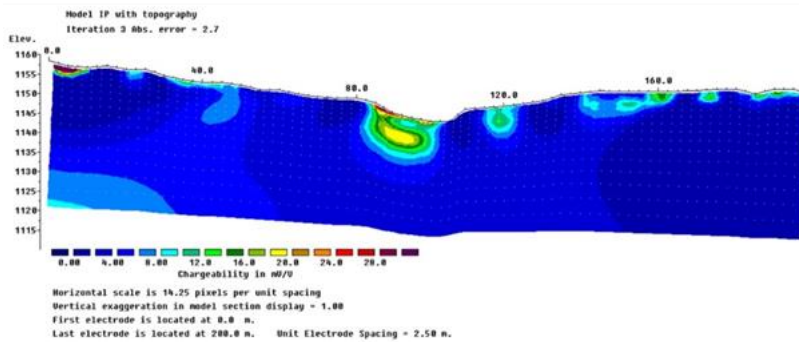
Perpendicular. E1 = US

Schlumberger IP 2023



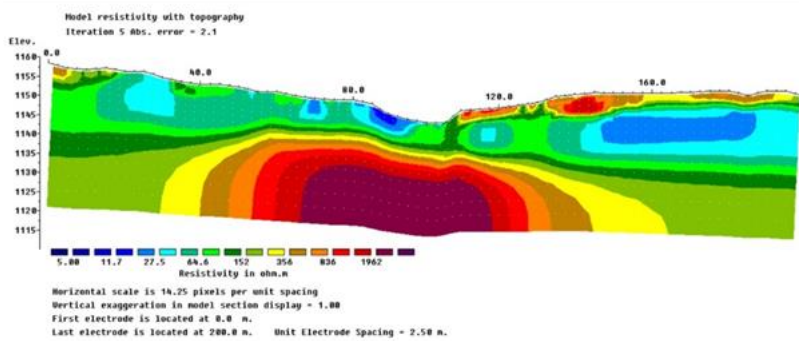
JUS. E1 = LHS

Gradient res 2022



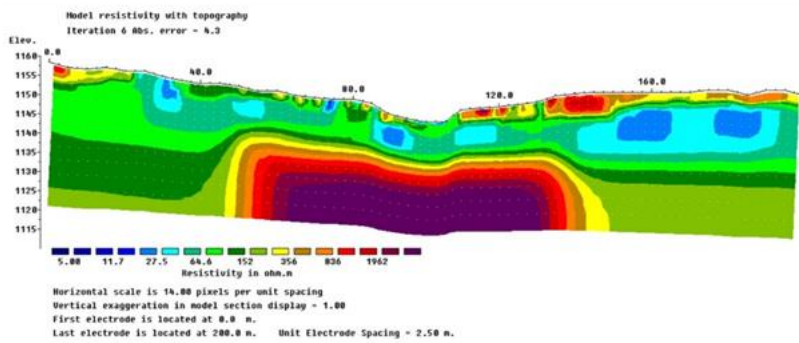
JUS. E1 = LHS

Gradient IP 2022



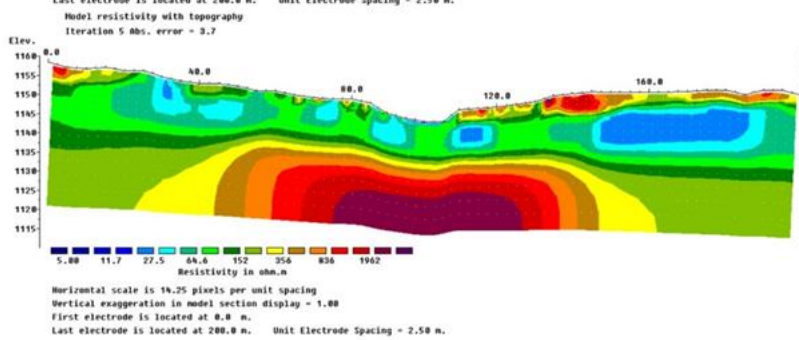
JUS. E1 = LHS

Schlumberger 2022



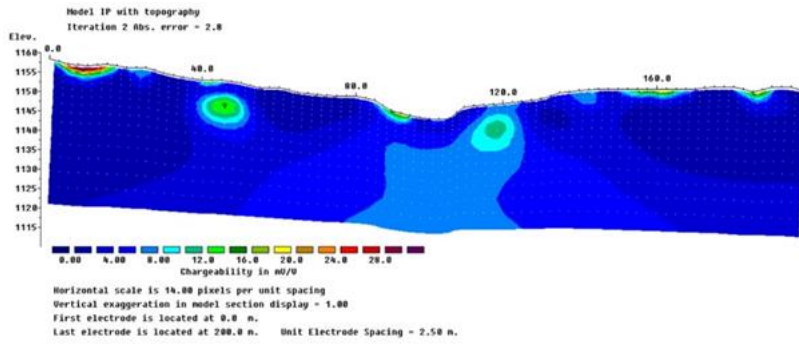
JUS. E1 = LHS

Gradient res 2023



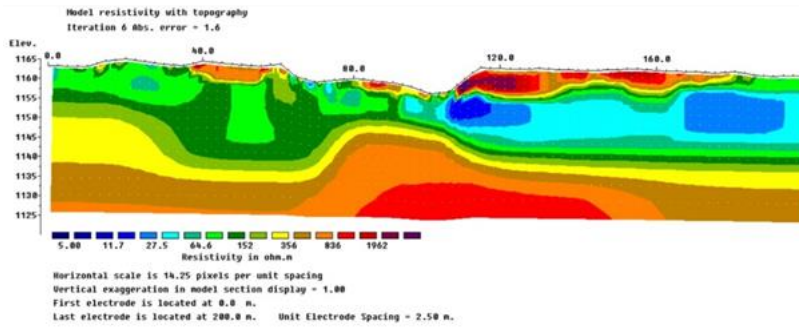
JUS. E1 = LHS

Schlumberger res 2023



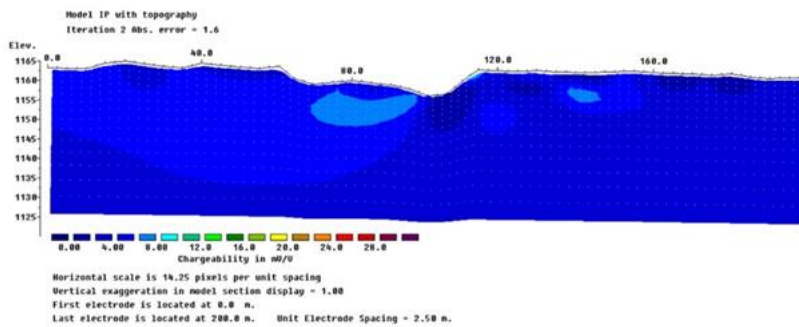
JUS. E1 = LHS

Schlumberger IP 2023



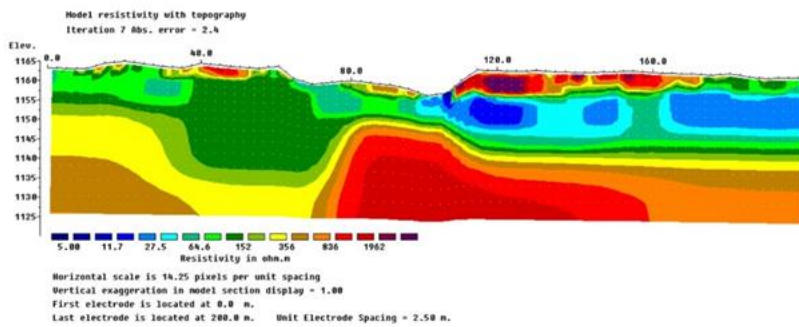
FUS. E1 = LHS

Gradient res 2022



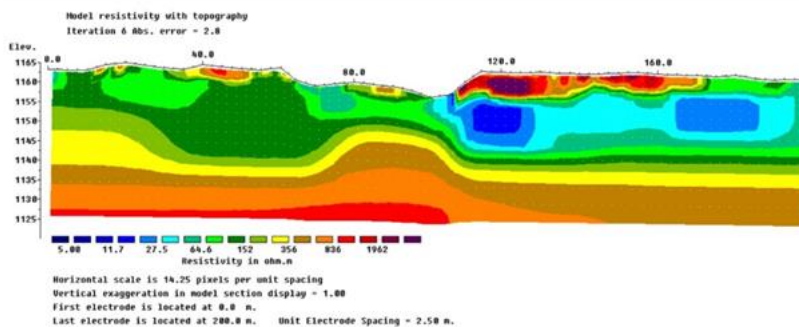
FUS. E1 = LHS

Gradient IP 2022



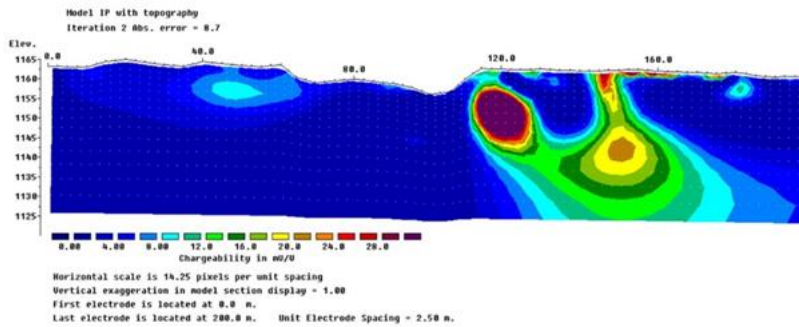
FUS. E1 = LHS

Gradient res 2023



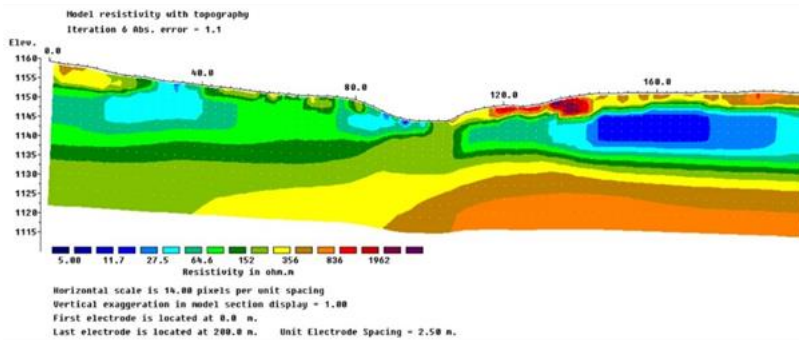
FUS. E1 = LHS

Schlumberger res 2023



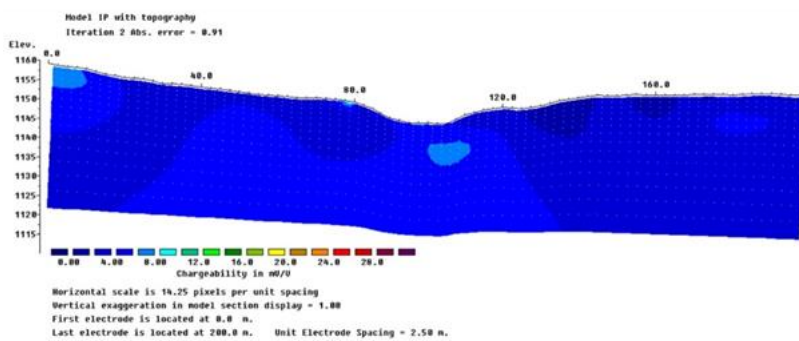
FUS. E1 = LHS

Schlumberger IP 2023



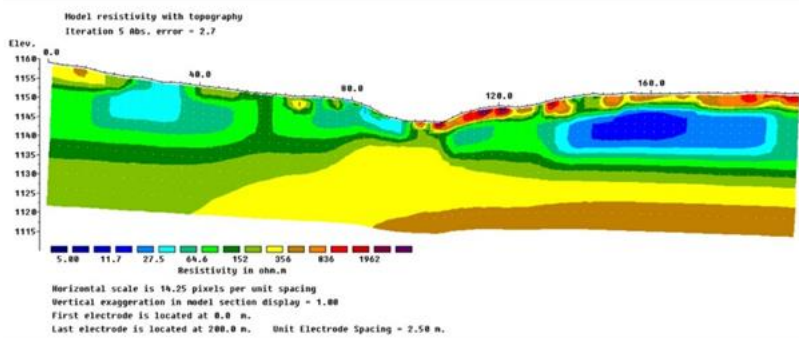
DS. E1 = LHS

Gradient res 2022



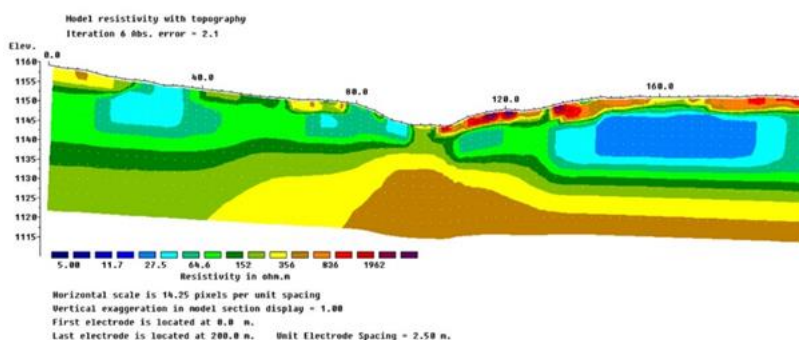
DS. E1 = LHS

Gradient IP 2022



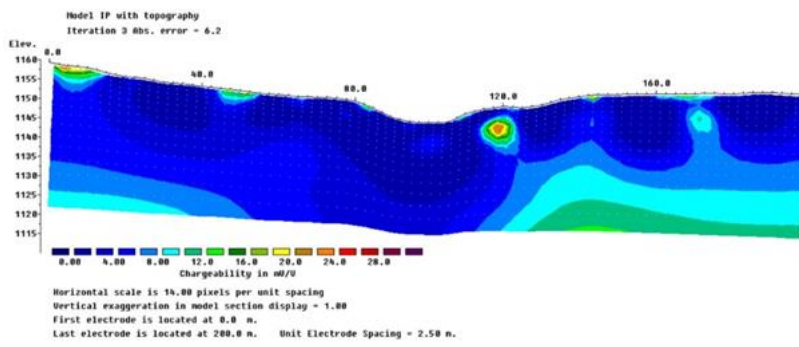
DS. E1 = LHS

Gradient res 2023



DS. E1 = LHS

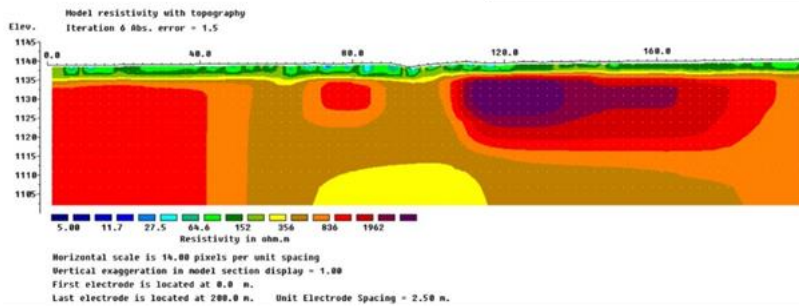
Schlumberger res 2023



DS. E1 = LHS

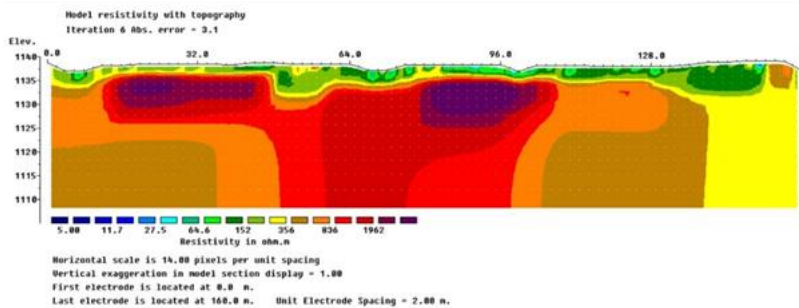
Schlumberger IP 2023

Wambiti



Perpendicular. E1 = DS

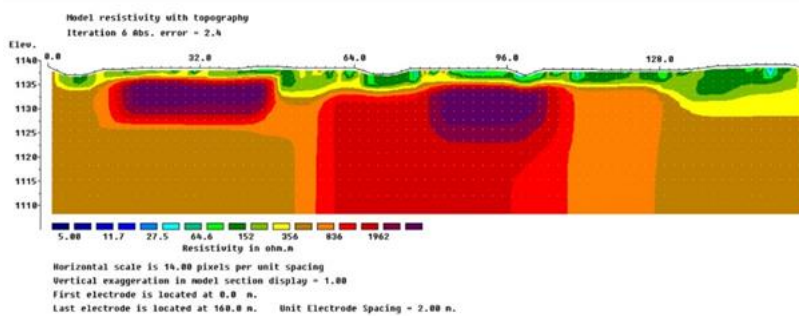
Gradient res 2022



Perpendicular DS. E1 = far

DS

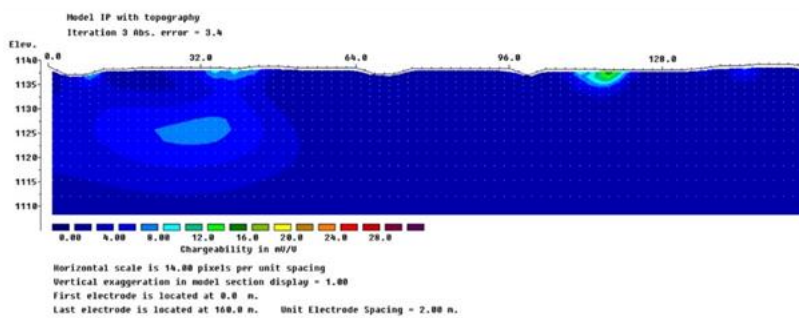
Gradient res 2023



Perpendicular DS. E1 = far

DS

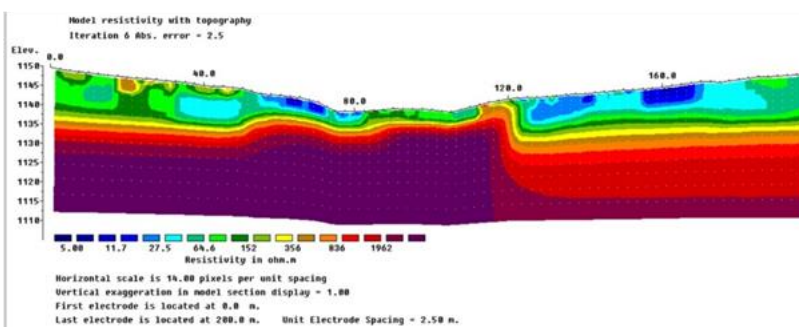
Schlumberger res 2023



Perpendicular DS. E1 = far

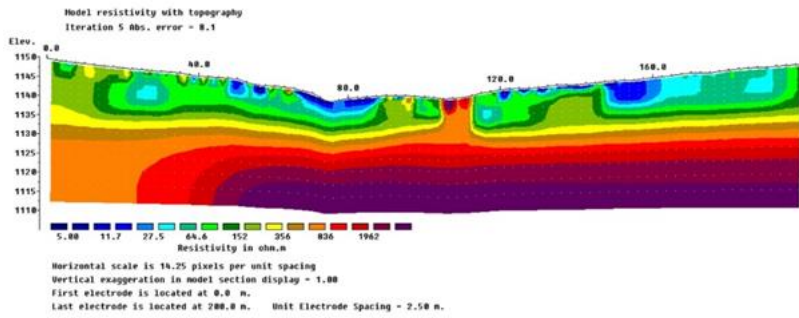
DS

Schlumberger IP 2023



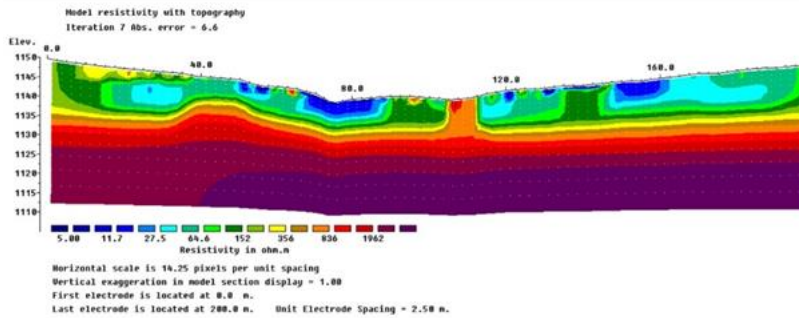
JUS. E1 = LHS

Gradient res 2022



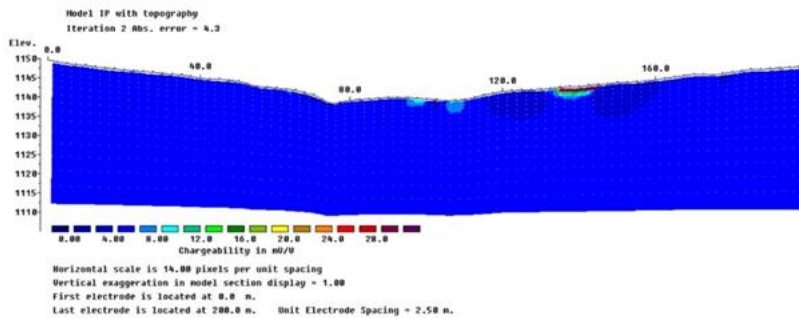
JUS. E1 = LHS

Gradient res 2023



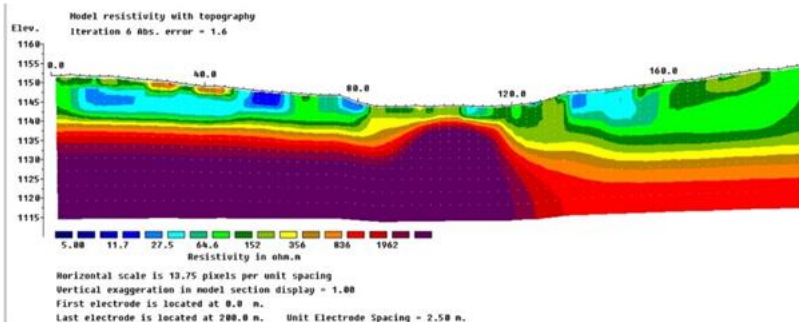
JUS. E1 = LHS

Schlumberger res 2023



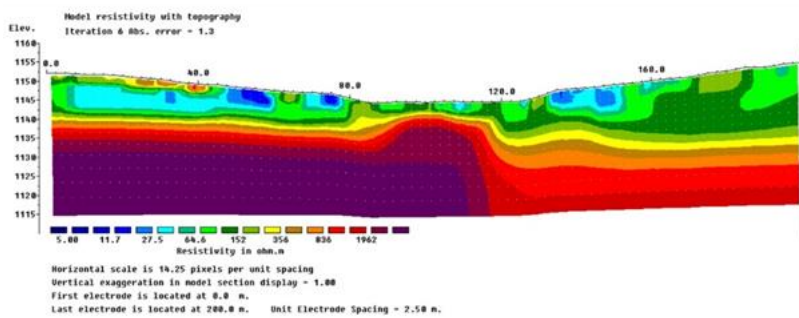
JUS. E1 = LHS

Schlumberger IP 2023



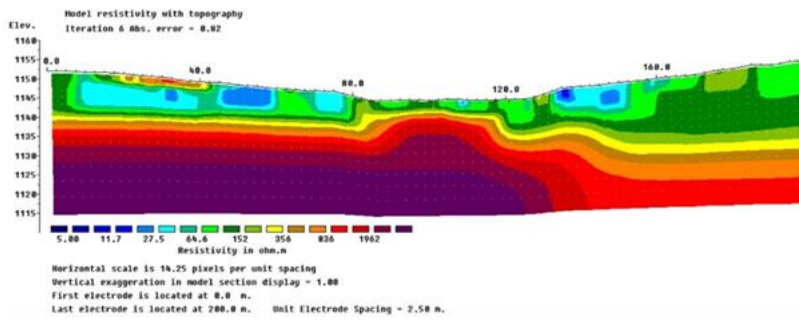
FUS. E1 = LHS

Gradient res 2022



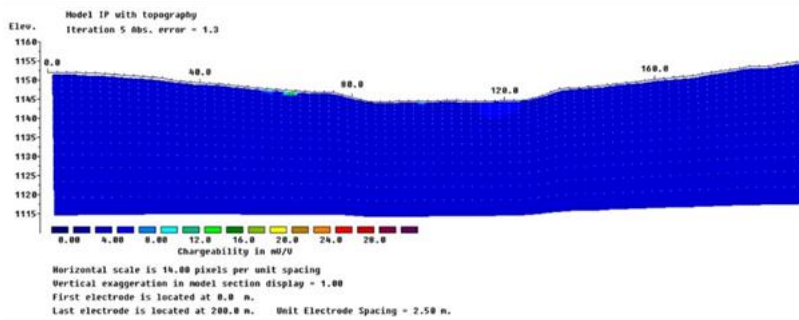
FUS. E1 = LHS

Gradient res 2023



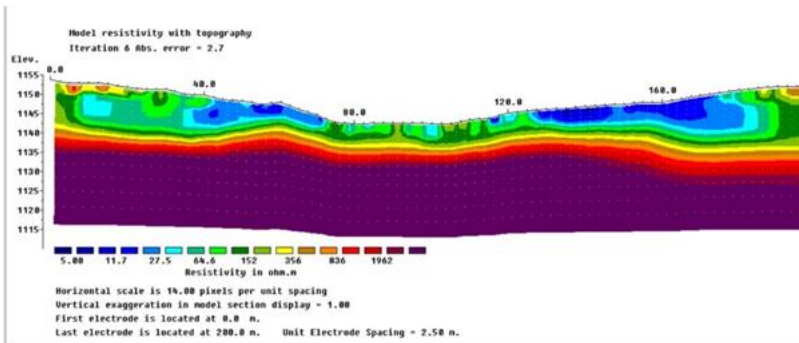
FUS. E1 = LHS

Schlumberger res 2023



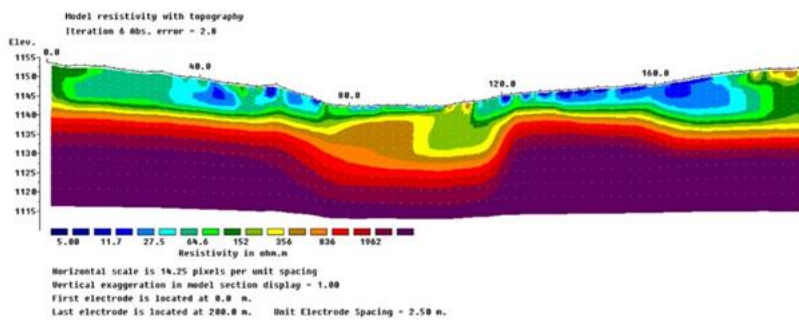
FUS. E1 = LHS

Schlumberger IP 2023



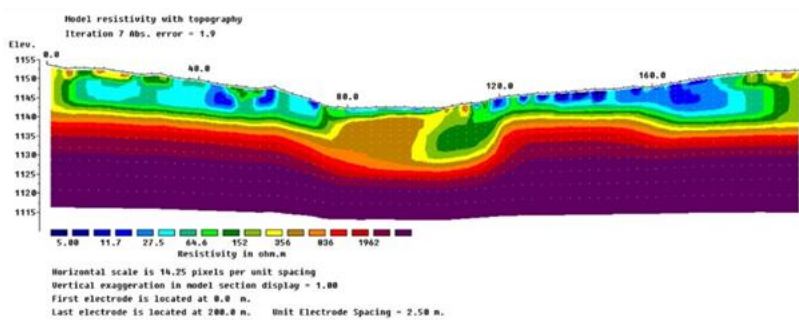
DS. E1 = LHS

Gradient res 2022



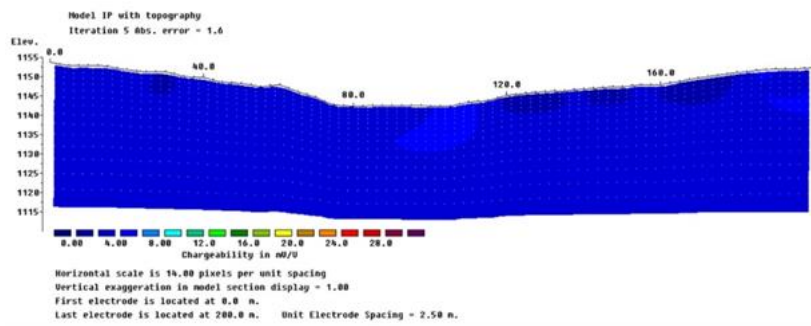
DS. E1 = LHS

Gradient res 2023



DS. E1 = LHS

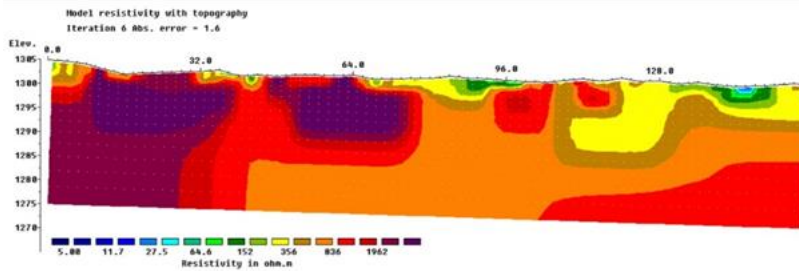
Schlumberger res 2023



DS. E1 = LHS

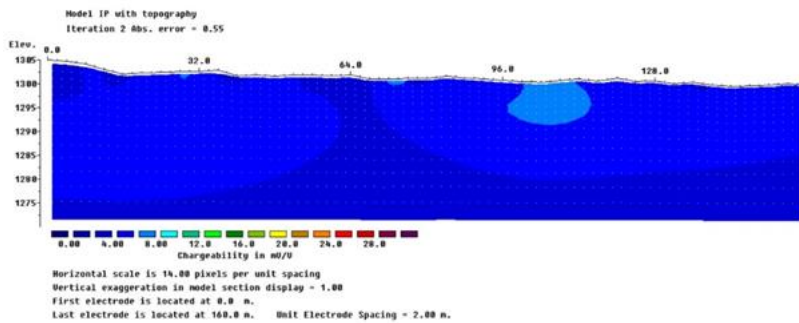
Schlumberger IP 2023

Kyakivandi



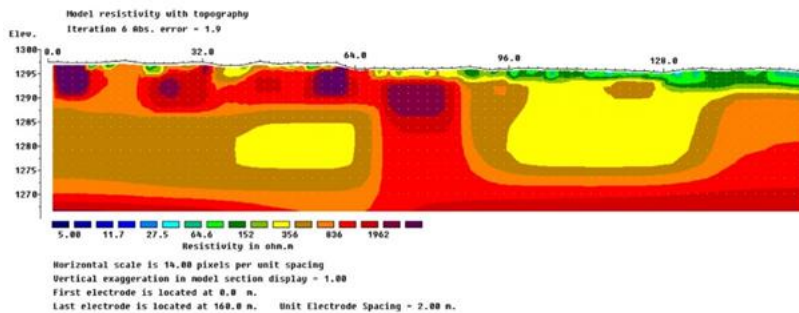
Perpendicular US. E1 =
FUS

Gradient res 2022



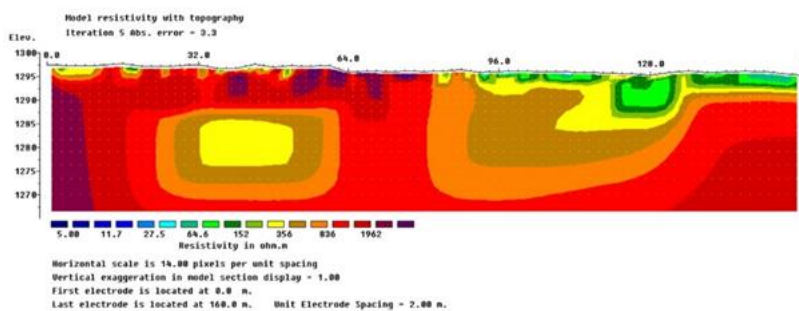
Perpendicular US. E1 =
FUS

Gradient IP 2022



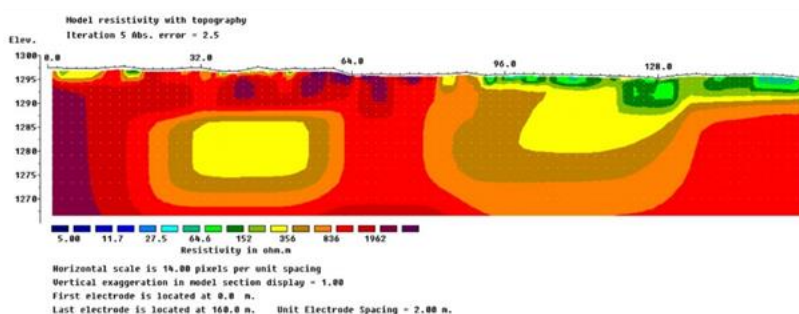
Perpendicular DS. E1 =
JDS

Gradient res 2022



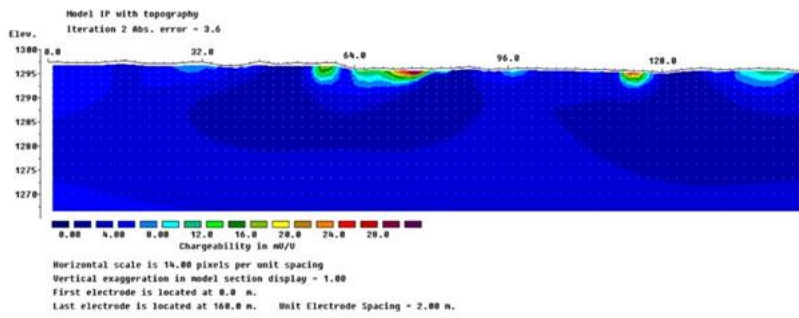
Perpendicular DS. E1 =
JDS

Gradient res 2023



Perpendicular DS. E1 =
JDS

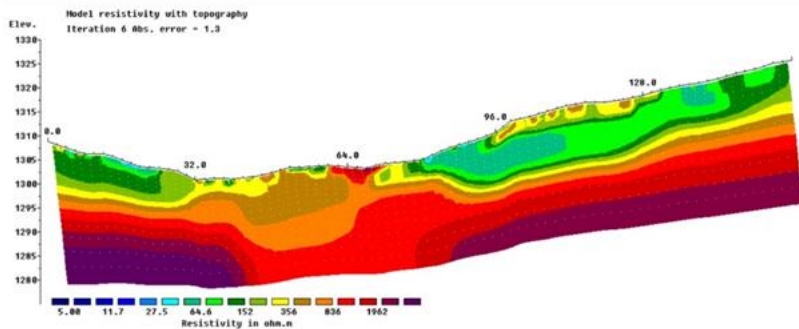
Schlumberger res 2023



Perpendicular DS. E1 =

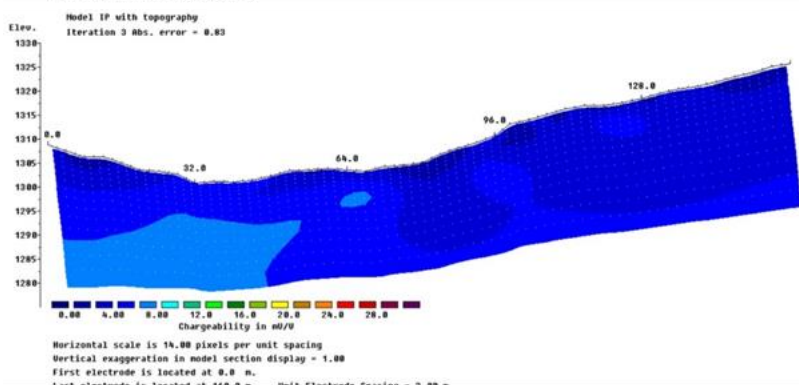
JDS

Schlumberger IP 2023



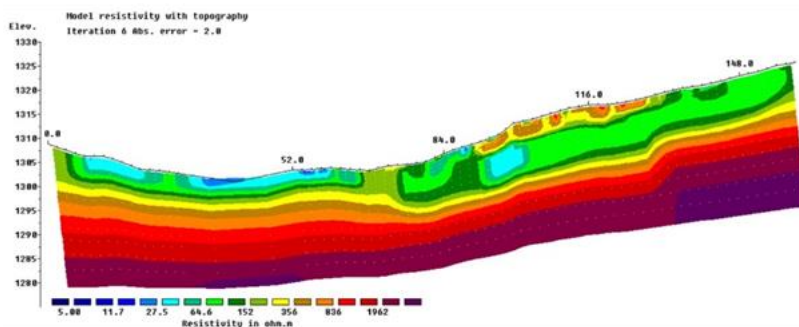
JUS. E1 = LHS

Gradient res 2022



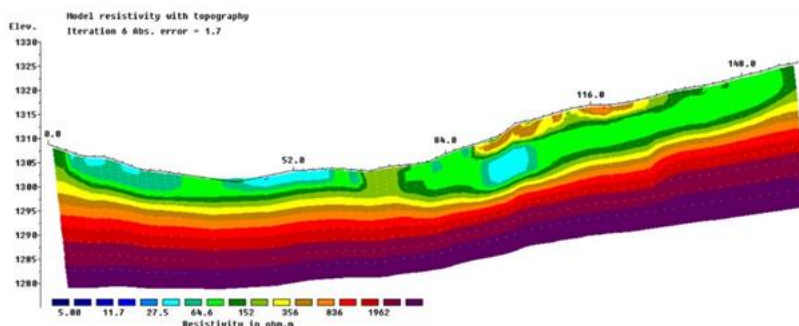
JUS. E1 = LHS

Gradient IP 2022



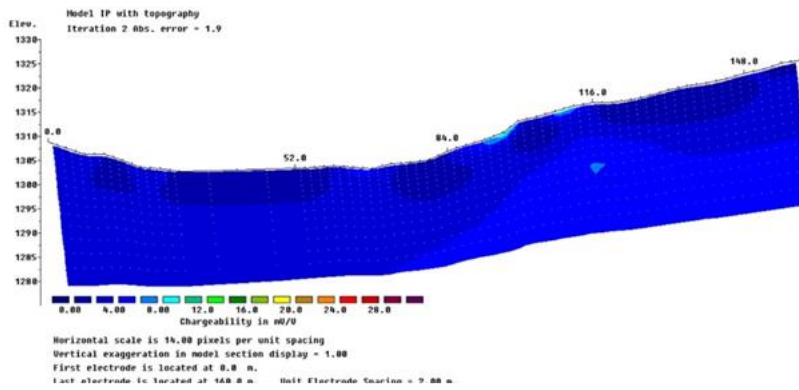
JUS. E1 = LHS

Gradient res 2023



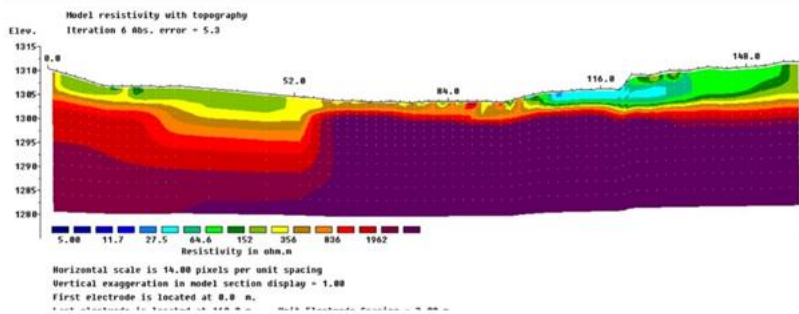
JUS. E1 = LHS

Schlumberger res 2023



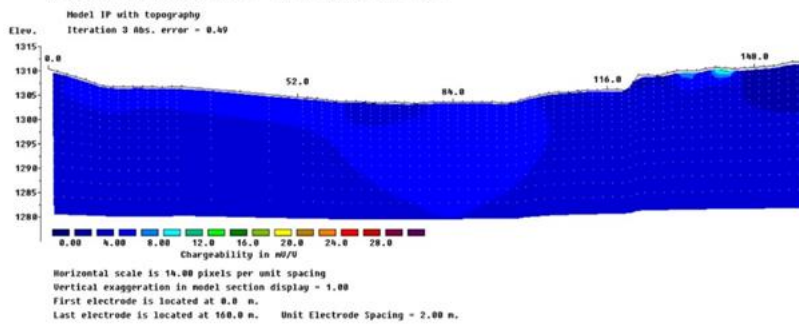
JUS. E1 = LHS

Schlumberger IP 2023



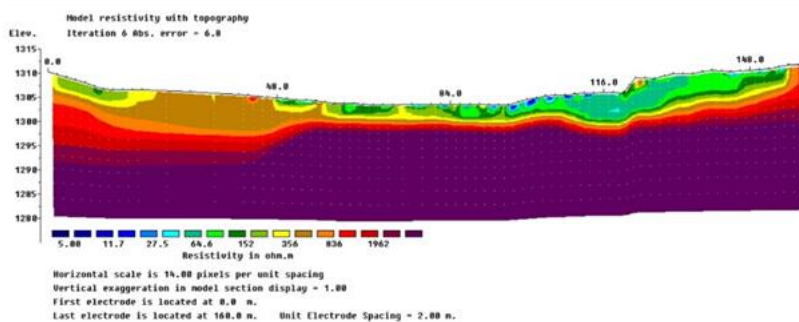
FUS. E1 = LHS

Gradient res 2022



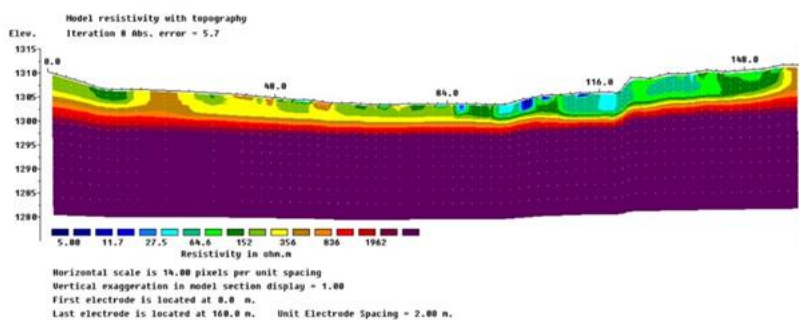
FUS. E1 = LHS

Gradient IP 2022



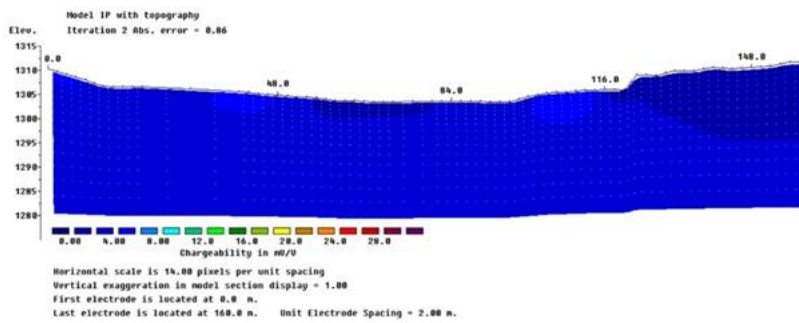
FUS. E1 = LHS

Gradient res 2023



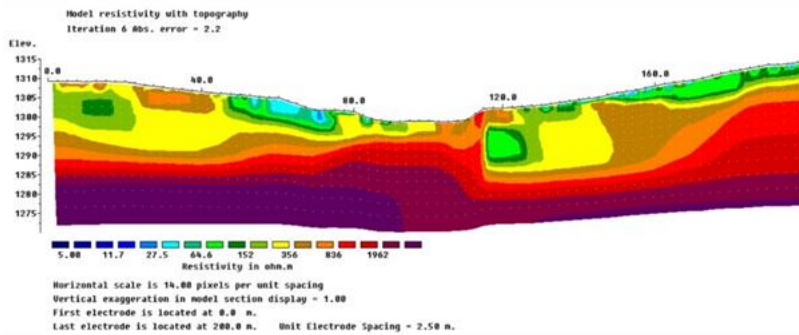
FUS. E1 = LHS

Schlumberger res 2023



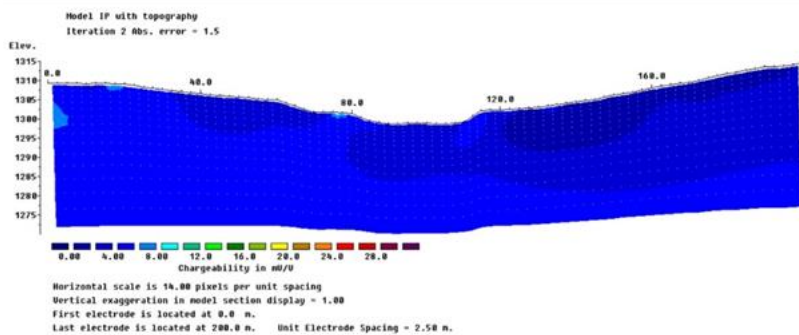
FUS. E1 = LHS

Schlumberger IP 2023



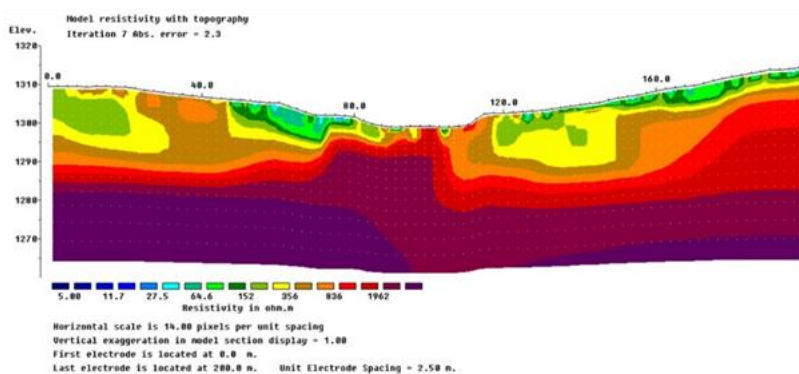
DS. E1 = LHS

Gradient res 2022



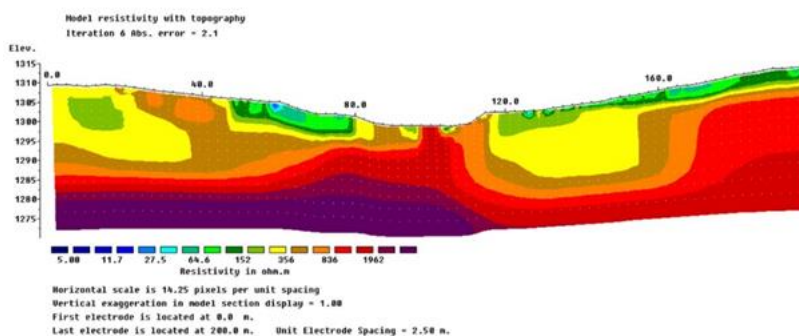
DS. E1 = LHS

Gradient IP 2022



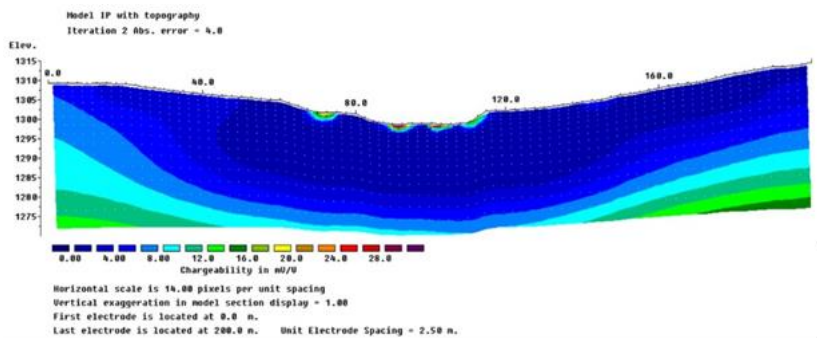
DS. E1 = LHS

Gradient res 2023



DS. E1 = LHS

Schlumberger res 2023



DS. E1 = LHS

Schlumberger IP 2023

Appendix G: Geophysics profiles

Appendix H Soil profiles

Kithunthi

Location	Electrode location on geophysics profile	Depth (m bgl)	Description
Scoop hole 5 m upstream	E30 profile 4	0-0.2	Very loose beige slightly gravelly coarse sand
		0.2-2.85	Light brown medium - coarse sand
		>2.85	Very soft very sandy clay
Scoop hole 20 m upstream	E27 profile 4	0-0.2	Very loose beige slightly gravelly coarse sand
		0.2-0.35	Light brown medium - coarse sand with fragments of gneiss
		>0.35	Damp grey medium - coarse sand with fragments of very soft very sandy blackish clay
Scoop hole 50 m upstream	E21 profile 4	0-0.1	Very loose moderately well sorted slightly gravelly coarse sand.
		0.1-0.9	Brown medium - coarse sand with black organic fragments
Scoop hole 5 m downstream	E32 profile 4	0-0.25	Very loose brown medium - coarse sand

		0.25-0.55	Grey coarse sand with fragments of very soft very sandy clay and roots
Scoop hole 45 m downstream	E21 profile 1	0-0.05	Soft brown sandy clay
		0.05-0.4	Brown coarse sand
Scoop hole 45 m downstream	E22 profile 1	0-0.25	Topsoil of dry, slightly gravelly medium sand
		0.25-0.5	Soft brownish grey sandy clay with pockets of coarse sand
		0.5-1.3	Clayey medium - coarse sand with cobbly and gravelly (quartz) past 0.7m and fragments of soft grey sandy clay
Scoop hole 20 m downstream	E35 profile 4	0-0.05	Soft dark brown sandy clay
		0.05-0.22	Slightly clayey coarse sand
Auger 45 m downstream 8-10 m into left bank	Profile 1	0-0.2	Topsoil - light brown gravelly fine – coarse sand with very sporadic cobbles of bricks
		0.2-0.9	Loose light brown slightly gravelly fine – coarse sand
		0.9-1.1	Same but slightly damp
		1.1-1.35	Slightly damp greyish brown loamy slightly gravelly slightly clayey fine – coarse sand

		1.35-2	Loose greyish light brown slightly gravelly fine – coarse sand
		2-2.22	Loose greyish brown loam. Stopped as could not penetrate rock
Auger 45 m downstream 8-10 m into right bank	Profile 1	0-0.1	Dark grey sandy clay
		0.1-0.5	Loose dark brown medium sand
		0.5-0.9	Mixed horizon of loose black and brown fine – coarse sand and soft black sandy clay
		0.9-1.1	Damp gravelly fine – coarse sand
		1.1-1.6	Greyish brown clayey coarse sand
Auger 120 m upstream 24-28 m into right bank	Profile 3	0-0.2	Topsoil - dark brown loam
		0.2-1.2	Very stiff blackish dark brown clay with high organic content. Same to depth
Auger 120 m upstream 24-28 m into left bank	Profile 3	0-0.1	Topsoil - greyish brown fine – coarse sand
		0.1-0.4	Reddish light brown fine – coarse sand
		0.4-1	Same but slightly damp and slightly gravelly
		1-1.4	Soft brown clayey fine clayey loam

Auger 20 m upstream	E31 profile 2	0-0.1	Reddish light brown fine – coarse sand
		0.1-0.4	Moderately soft reddish very dark brown sandy clay
		0.4-0.6	Moderately stiff reddish very dark brown slightly sandy clay
		0.6-1	Moderately soft reddish very dark brown very sandy clay
		1-1.1	Same

Kipico

Location	Electrode location on geophysics profile	Depth (m bgl)	Description
Scoop hole immediately upstream	E6 profile 4	0-0.12	Hard silty slightly gravelly coarse sand
		0.12-0.54	Brown slightly gravelly coarse sand
		0.54-0.64	Soft dark brown sandy clay
		0.64	Coarse sand
Scoop hole 9m upstream	E8 profile 4	0-0.06	Coarse slightly gravelly sand
		0.06-0.9	Loose brown coarse sand

		0.9-1.05	Soft reddy brown slightly sandy clay with organic smell
		1.05-1.5	Soft reddy brownny dark grey organic sandy clay
		1.5-1.55	Dark brown medium sand
		1.55-1.6	Damp brown dark greyish sandy clay
		1.6-1.62	Greyish reddish dark brown clayey fine - medium sand
		1.62-2.1	Soft blackish brownish reddish very dark grey sandy clay
		2.1-3.4	Well sorted greyish blackish dark brown coarse sand
		3.4	Hard rock hit
Scoop hole 110 m upstream	E28 profile 4	0-1.3	Coarse gravelly sand
		1.3-1.4	Slightly clayey medium sand
		1.4-1.55	Soft sandy clay
		1.55-2.2	Well sorted brownny red coarse gravelly sand
Scoop hole 2.1 m downstream	E5 profile 4	0-0.6	Slightly gravelly coarse sand
		0.6	Quartzite
		0.6-0.85	Damp black coarse sand
Scoop hole 16 m downstream	E21 profile 1	0-0.6	Slightly gravelly coarse sand
		0.6-0.9	Gneiss

Auger 9 m upstream	E36 profile 2	0-0.2	Topsoil – greyish light brown red tinged clayey loam with slightly gravelly fine – coarse sand grains with some gravels of pegmatite
		0.2-0.45	Reddish brown clay loam with fine – very coarse sand grains
		0.45-0.7	Moderately dense dark reddish brown sandy cobbly gravel. Same to depth. No dampness
Auger 9 m upstream	E39 profile 2	0-0.3	Topsoil - moderately dense greyish brown sandy cobbly gravel
		0.3-depth	moderately dense dark reddish brown fine – very coarse sand. No dampness
Ravine profile 145 m upstream		0-0.8	Brown sandy slightly gravelly fine-coarse loam
		0.8-1.5	Moderately dense dark reddish brown sandy cobbly gravel
		1.5-depth	Weathered gneiss
Auger 9 m upstream 4 m into left bank	Profile 2	0-0.15	Moderately loose light brown fine – coarse sand
		0.15-0.5	Moderately loose reddish brown sandy predominantly fine silt
		0.5-0.7	Slightly weathered gneiss and silt

		0.7-1.1	Slightly weathered gneiss in brown slightly clayey silt
		1.1-1.8	Reddish darker brown silty sandy gravelly loam grades into clayey loam and then sandy loam with areas of slightly weathered gneiss
		1.8- depth	Slightly weathered gneiss
Scoop hole	E35 profile 4	0-0.5	Very loose light brown fine – very coarse sand with slightly gravelly hard baked bits of sand with black layers (iron), gravel and cobbles of quartz and gneiss
		0.5-1.6	Very loose brown slightly clayey slightly gravelly fine – very coarse sand with dominant slightly clayey silt layer 1.45 – 1.65
		1.6-1.65	Moderately soft greyish dark brown and black mottled with red silty clay
		1.65-1.8	Brown slightly gravelly fine – very coarse sand
		1.8-1.9	Brown with mottled of black gravelly, cobbly fine – coarse sand,
		1.9- depth	Un-weathered gneiss in half of hole. In other half you have reddish brown silt and fine – coarse loose sand

Scoop hole	E17 profile 4	0-0.11	Very loose beige slightly gravelly fine – very coarse sand
		0.11-0.46	Damp loose brown fine – very coarse sand with baked parts and black iron layers
		0.46-0.55	Blackish brown mottled red silt
		0.55-1.9	Black tinged brown silty fine sand
		1.9-depth	Loose fine – very coarse sand

Ngulai

Location	Electrode location on geophysics profile	Depth (m bgl)	Description
Scoop hole 150 m upstream	E21 profile 3	0-0.9	Moderately well sorted light brown gravelly very coarse sand
		0.9-1.1	Reddish dark brown slightly clayey medium sand with layers of very soft dark brown blackish sandy clay
		1.1-1.5	Gravelly clayey very coarse sand
		1.5-3.5	Coarse sand
		>3.5	Bedrock

Scoop hole 9 m upstream	E22 in profile 2	0-0.4	Slightly gravelly slightly silty sand
		0.4-0.85	Brown gravelly coarse sand
		0.85-1	Soft brownish reddish grey sandy clay
		1-1.6	Dark brown slightly clayey coarse sand
Dug pit 9 m upstream 8 m into left bank	E17 profile 2	0-0.02	Topsoil - loose reddish brown fine – very coarse sand
		0.02-0.1	Silt
		0.1-0.3	Brown slightly clayey silty slightly gravelly fine – coarse sand – sandy loam.
		0.3-0.5	Silt and weathered rock
		0.5-0.7	Loose sand
		0.7-1.1	Silt. Slightly damp after 1 m
		1.1-1.6	Soft red mottling dark brown very silty sandy clay
		1.6-2.1	Brownish grey clayey silty fine – coarse sand
Dug pit 9 m upstream 36 m into right bank	E32 profile 2	0-0.3	Reddish brown silty sandy loam with bits of bark and roots
		0.3-depth	Unweathered gneiss. No dampness
13.5 m downstream	E11 profile 1	0-0.02	Topsoil - brick colour sandy loam with roots

		0.02-0.25	Brick colour clayey loam with roots
		0.25-0.7	Brick colour very gravelly cobbly fine – very coarse sand, with fragments of weathered gneiss. No dampness
150 m upstream 64 m into right bank	E38 profile 3	0-0.45	Dry dense brick reddish brown loamy fine – medium sand with tree and plant roots
		0.45-0.6	Stiff brick reddish brown sandy clay
		0.6-1.1	Dry moderately stiff brick coloured clayey fine-coarse loam
		1.1-depth	Same to depth. No dampness

Nthonzweni

Location	Electrode location on geophysics profile	Depth (m bgl)	Description
Right hand side upstream wing wall	E22 profile 2	0-0.1	Topsoil – Dense moderately well sorted reddish brown gravelly cobbly coarse sand with weathered rock fragments >10cm

		0.1-2	Browny grey sandy clay
		2-5.0	Poorly sorted coarse sub-angular beige grey sand. Horizon at 3m of gravels. Approx. 10cm thick grey sandy clay layers interspersed. Well sorted clayey sand at 3.5m
		5.0-6.7	Browny grey silty sandy coarse clay
		Approx. 7.3m	Bedrock (weathered gneiss)
Tank 20 m upstream	E21 profile 2	0-0.1	Beige very loose sand
		0.1-0.84	Silty coarse sandy grey clay mainly, although some layers are less clayey and are clayey sand. Interspersed with weathered bedrock (saprolite) with red and orange weathering
Auger 20 m downstream 40 m into right bank	Profile 1	0-1	Very loose brown slightly clayey silty slightly gravelly sand
Auger 20 m downstream 50 m into left bank	Profile 1	0-0.05	Red silty slightly clayey very gravelly fine sand
		0.05-0.2	Soft reddish brown sandy slightly gravelly clay
		0.2-0.4	Moderately stiff reddish dark brown slightly sandy slightly gravelly clay
		0.4-0.65	Same but very slightly stiffer

Auger 95 m upstream 32 m into left bank	Profile 3	0-0.2	Dark brown very sandy clay
		0.2-1	very soft dark brown sandy clay
		1-1.5	Moderately stiff brown sandy slightly gravelly clay
Auger 5 m upstream 30 m into right bank	Profile 2	0-0.15	Topsoil - dark brown sand
		0.15-0.7	Slightly damp very soft dark brown very sandy clay
Scoop hole 5 m downstream		0-0.25	Moderately stiff orange and grey sandy clay
		0.25-depth	Bedrock

Wambiti

Location	Electrode location on geophysics profile	Depth (m bgl)	Description
Left hand side wing wall upstream	E9 profile 2	0-1	Topsoil - hard ground. Reddy brown silty sandy slightly gravelly soft clay
		1-1.1	Fine slightly gravelly sand
		1.1-1.95	Weathered gneiss

Right hand side bank in wing wall upstream	E26 profile 2	0-0.6	Topsoil - hard ground. Reddy brown silty sandy slightly gravelly soft clay
		>0.6	Weathered gneiss
Left hand side bank in wing wall upstream	E24 profile 2	0-2.2	Topsoil - Reddy brown silty sandy slightly gravelly soft clay
		>2.2	Sand
Just upstream wall construction	E22 profile 2	0-0.15	Topsoil - loose beige coarse gravelly sand
		0.15-0.35	Loose brown coarse gravelly sand
		0.35-1.1	Well sorted grey very clayey coarse sand
		1.1-3	Grey clayey coarse gravelly sand
		>3	Bedrock. Some areas just before bedrock you have very gravelly sand (gravels rounded and up to 5cm)
Scoop hole 110 m upstream	E21 profile 3	0-1.1	Very loose moderately poorly sorted beige slightly gravelly coarse sand
Auger 110 m upstream on left hand side bank	E15 profile 3	0-1.1	Brown very soft sandy clay
		1.1-1.45	Stiff dark brown clay

Scoop hole 15 m downstream	E16 profile 1	0-0.65	Moderately poorly sorted beige very gravelly very coarse sand (damp after 0.1m)
Auger 15 m downstream	E31 profile 1	0-0.7	Very soft reddy brown very sandy clay
		0.7-1.18	Soft reddy brown sandy clay. Less sandy and slightly stiffer than above
Auger 10 m upstream	E8 profile 2	0-0.9	Topsoil - very red organic sandy clay
		0.9-1.2	Moderately soft brownish red gravelly sandy clay
Auger 190 m upstream		0-0.5	Dry reddy brown clayey loam
		0.5-0.6	Brown clayey, silty, sandy gravel (2 – 5cm) of mostly quartzite
		0.6-1	Soft brown gravelly sandy clay
Auger 10 m upstream	E5 profile 2	0-0.4	Very dense reddy brown sandy clayey loam
		0.4-1.2	Moderately dense brick red sandy clayey silt with small roots

Kyakivandi

Location	Electrode location on geophysics profile	Depth (m bgl)	Description

Left hand side riverbank 65 m downstream	E18 profile 1	0-0.2	Topsoil - loose well sorted red slightly gravelly medium - coarse sand with mica
		0.2-2.5	Red gravelly coarse sand with laminated layers of gravels
Left hand side wing wall		0-0.2	Topsoil - sand
		0.2-3.5	Very soft very sandy red clay. 1m bgl is a 10cm thick layer of rounded gravels and cobbles
		3.5-3.7	Clay
		3.7	Bedrock - unweathered gneiss
Scoop hole 45 m upstream	E10 profile 2	0-0.2	Very loose beige gravelly cobbly coarse sand with large fragments of soft grey sandy clay. At 0.2m there is some weathered gneiss. 70% sand, 30% clay. Not distinct layers
		0.2-0.75	Coarse sand
		0.75	Rock - unweathered gneiss
Scoop hole 140 m upstream	E22 profile 3	0-0.15	Very loose slightly gravelly coarse sand
		0.15-1.15	Greyish blackish brown gravelly slightly cobbly coarse sand with fragments of soft grey very sandy clay. Especially gravelly and cobbly 0.15-0.35
		1.15	Rock
	E23 profile 4	0-0.3	Very loose beige gravelly medium sand

Scoop hole 92 m upstream		0.3-0.5	Damp brown slightly clayey slightly gravelly coarse sand
		0.5-0.9	Black clayey coarse sand
		0.9-1.05	Brown and black slightly clayey gravelly coarse sand
		1.7	Rock
Scoop hole 108 m downstream	E29 profile 4	0-0.2	Very loose beige cobbly coarse sand
		0.2-0.3	Brown and black gravelly cobbly very coarse sand
		0.3-0.4	Grey coarse sand
		0.4	Brown and black gravelly cobbly very coarse sand
Scoop hole 65 m downstream	E20 profile 1	0-0.2	Very loose beige slightly gravelly coarse sand
		0.2-0.5	Damp brown very gravelly cobbly coarse sand
		0.5-1.35	Greyish brown slightly gravelly coarse sand
		1.35	Rock
Scoop hole 36 m downstream	E11 profile 4	0-0.35	Very loose light brown coarse sand
		0.35-0.86	Gravelly slightly cobbly very coarse sand
		0.86	Rock
Auger 45 m upstream	E7 profile 2	0-0.1	Topsoil – damp moderately soft dark brown silty sandy clay

		0.1-0.7	Very loose dark brown sandy loam with roots
		0.7-0.8	Loam
		0.8-1.5	Very loose brown slightly clayey medium – coarse sand
		1.5-2.05	Greyish brown clayey sandy loam. Stopped because hit rock
Dug pit 65 m downstream	E36 profile 1	0-0.2	Topsoil - dark brown slightly clayey slightly gravelly fine – coarse sand with roots
		0.2-0.85	Very dark brown sandy fine-coarse loam with small chunks of soft reddish clay
Auger 45 m upstream	E17 profile 2	0-0.2	Dry soft red sandy clay with roots
		0.2-0.85	Damp reddish brown very sandy soft clay
		0.85-1.25	Very soft reddish dark brown and black slightly gravelly clayey silty sandy loam
		1.25-depth	Unweathered gneiss
Auger 45 m upstream	E31 profile 2	0-0.4	Soft reddish dark brown gravelly cobbly sandy clay (gravels of predominantly quartz)
		0.4-0.6	Red aggregate gravels and cobbles of quartz and very weathered gneiss and schists in sandy soft clay

Auger 140 m upstream	E29 profile 3	0-0.1	Topsoil – loose light brown gravelly fine – coarse sand
		0.1-0.27	Reddish brown slightly clayey gravelly (brick) fine – very coarse sand
		0.27-0.67	Dark mottled brownish red slightly clayey very gravelly and cobbly (brick) fine – very coarse sand.
		0.67-0.95	Dark brown – black slightly clayey slightly gravelly fine – coarse sand

Appendix H: Soil profiles taken in scoop, dug, and augered holes and during wall construction at each site in order to help inform geophysical interpretations

Appendix I Irrigation survey

Questions

- 1.) Which portion of land do you work?
- 2.) When was the last time that you watered your crops?
- 3.) For what duration did you irrigate your crops?
- 4.) How often do you usually water your crops?
- 5.) For what duration do you usually irrigate your crops?

Answers

Kipico

Location of irrigated land on inversion profiles	Just upstream: E2 – E7 Downstream: E5.5 – E7.5 and E11 – E16.5
Duration of watering	4 hours
Frequency of watering	Once per week
Area of irrigated land	Area of irrigated land

Nthonzweni

Location of irrigated land on inversion profiles	Big corn field on left hand side Just upstream: E1 – 9 Downstream: E1-10
Date of watering	Watered on 8 th , middle and end of January and won't irrigate again this season (1 month ago)

Location of irrigated land on inversion profiles	RHS oranges and mangoes all the way along the riverbank Just upstream: E27-41 Far upstream: E24-41
Frequency of irrigation	2 days per week Won't irrigate everything every 2 days. Would do say Mangoes one day, and then

	two days later do oranges etc. so that everything gets watered approximately once / week
Date of watering	Last irrigated on Tuesday (interviewed on Thursday) Just irrigates in the dry season
Duration of irrigation	3 – 4 hours

Wambiti

Location of irrigated land on inversion profiles	Right hand side Far upstream: E37-41
Date of watering	One day ago (04.03.23)
Frequency of irrigation	Waters different crops between every day – every 4 days
Duration of irrigation	Waters crops for 5 hours at a time
Amount of water	Uses a water pump Uses approx. 1000L / 5 hours
Area of irrigated land	Waters an area of 0.5 acres

Kyakivandi

Location of irrigated land on inversion profiles	Just upstream: Irrigated from the bed to approx. 8m from the top of the bank. E3 – E8 (8 – 28m)
Date of watering	Watered on date of interview (28.02.23 – Tuesday)
Duration of irrigation	Spends 2 hours on average watering crops
Frequency of irrigation	Waters them every day
Area of irrigated land	Approximately. 1/8 th of an acre
Amount of water	Uses on average 12 x 10L jerry cans per water.

Appendix IH: Irrigation survey: questions and answers

Appendix J Water level elevations: riverbed and weathered basement

Kithunthi

		Location upstream of dam wall (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)	Distance between measurement in riverbed and weathered basement (m)
1	Riverbed (start of short dry season)	20	99.887	0	99.887	4
	Riverbed (09/02/2023)			0.95	98.937	
	Weathered basement (09/02/2023)		100.124	2.25	98.794	

Kipico

		Location upstream of dam wall (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)	Distance between measurement in riverbed and weathered basement (m)
1	Riverbed (start of short dry season)	9	100.139	0	100.139	7
	Riverbed (15/02/2023)			2.19	97.949	
	Weathered basement (15/02/2023)		100.558	2.76	97.798	

Ngulai

		Location upstream of dam wall (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)	Distance between measurement in riverbed and weathered basement (m)
1	Riverbed (start of	9	100.026	0	100.026	20

	short dry season)					
	Riverbed (13/02/2023)			1.3	98.726	
	Weathered basement (13/02/2023)			102.019	2.08	99.939
2	Riverbed (start of short dry season)	150	100.566	0	100.566	20
	Riverbed (13/02/2023)			1.090	99.476	
	Weathered basement (13/02/2023)		100.304	1.520	98.784	

Kyakivandi

		Location upstream of dam wall (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)	Distance between measurement in riverbed and weathered basement (m)
1	Riverbed (start of short dry season)	45	100.000	0	100.000	16
	Riverbed (11/02/2023)		99.387	0	99.387	
	Weathered basement (11/02/2023)		99.017	0.85	98.167	
2	Riverbed (start of short dry season)	45	100.000	0	100.000	24
	Riverbed (11/02/2023)		99.387	0	99.387	
	Weathered basement (11/02/2023)		99.312	1.2	98.112	

Appendix J: Water level measurements in the riverbed (in scoop holes) and weathered basement (in a combination of disused shallow wells, agricultural wells which had not

been used for at least two days, and dug wells) used to calculate lateral hydraulic gradients at the start and mid-way through the short dry season.

Appendix K Water level elevations: upstream and downstream

Kithunthi

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
Upstream	300	100.592	0.595	99.997
	200	100.649	0.655	99.994
	120	100.094	1.030	99.064
	20	99.887	0.950	98.937
Wall	0	100		
Downstream	-3	96.895	0	96.895
	-45	96.883	0.360	96.523
	-120	95.735	0.420	95.315
	-125	94.889	0	94.889
	-200	94.812	0.540	94.272

Kipico

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
Upstream	400	102.671	2.840	99.831
	350	102.323	2.570	99.753
	300	101.974	2.300	99.674
	175	101.042	2.300	98.742
	55	100.422	2.200	98.222
	9	100.139	2.190	97.949
Wall	0	100		

Downstream	-2.5	97.208	0.730	96.478
	-17	97.019	0.700	96.319
	-30	96.921	0.695	96.226

Ngulai

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
Upstream	400	102.763	0.950	101.813
	300	102.299	0.920	101.379
	250	101.572	0.995	100.577
	200	100.844	1.070	99.774
	150	100.566	1.090	99.476
	100	100.603	1.450	99.153
	8.4	100.026	1.300	98.726
Wall	0	100		
Downstream	-1	96.700	0	96.700
	-10	96.653	0	96.653
	-50	95.018	0	95.018
	-100	94.112	0	94.112
	-200	93.260	0	93.260

Nthonzweni

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
	400	100.452	1.150	99.302
	300	99.594	0.481	99.113

Upstream	240	98.852	0.468	98.384
	200	98.880	0.449	98.431
	150	98.648	0.970	97.678
	115	98.076	0.440	97.636
	95	98.254	0.294	97.960
	50	98.002	0.050	97.952
	5	97.806	0.196	97.610
Wall	0	100		
Downstream	-10	96.623	0	96.623
	-20	96.955	0.335	96.620
	-70	96.732	0.450	96.282
	-100	96.499	0.700	95.799
	-200	95.791	0.065	95.726

Wambiti

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
Upstream	400	100.479	0.465	100.014
	300	100.138	0.505	99.633
	200	99.821	0.320	99.501
	110	99.387	0.309	99.078
	1	99.250	0	99.250
Wall	0	100		
	-2	97.305	0	97.305
	-15	97.802	0.400	97.402
	-80	97.407	0.390	97.017
	-100	97.757	0.610	97.147

Downstream	-145	97.437	0.650	96.787
	-175	97.021	0.510	96.511
	-200	97.518	0.750	96.768

Kyakivandi

	Location (m)	Surface level elevation (m)	Measured water level below surface (m)	Water level elevation (m)
Upstream	400	100.610	0.510	100.100
	300	100.457	0.550	99.907
	200	100.167	0.317	99.850
	140	100.090	0.250	99.840
	50	99.387	0	99.387
	1	99.387	0	99.387
Wall	0	100		
Downstream	-8	97.017	0.480	96.537
	-65	95.185	1.090	94.095
	-76	95.103	1.220	93.883
	-100	94.651	0.650	94.001
	-200	94.046	0.370	93.676

Appendix K: Water level elevations upstream and downstream of the dam wall at each site used to calculate longitudinal hydraulic gradients

Appendix L Vegetation interview

Questions

- 1) Has any of the vegetation (non-human induced) coverage here next to the trapped sand changed since sand dam construction?
- 2) Has any of the vegetation (non-human induced) coverage further away from the trapped sand changed since dam construction?
- 3) Has there been more noticeable change: a.) along the banks directly next to the riverbed, b.) further away from the riverbed, c.) the same?
- 4) Why has the vegetation changed? Has there been any human activity?
- 5) Has there been any noticeable change downstream or is it just upstream?

Answers

Kithunthi

Person 1

- 1) Before dam, area was so dry. WT rose. Trees used to shed their leaves. There was no grass. There was a small deep valley. Ground level in the bank was the same. Valley was 8 feet deep in the riverbed area, in the area before the fence, basically in the no grass area
- 2) There has been no change further away.
- 3) More change close by
- 4) More crops have been planted (upstream). This is just upstream, not downstream.
- 5) Downstream you have erosion in the riverbed. Sand is carried away. You have some grass in the bed. You have erosion in the banks. There's been no change in vegetation

Person 2

- 1) Its now green all of the time (upstream). Before, it was dry, with no vegetation

- 2) There's been no change further up in the bank
- 3) There has been more change next to the bed
- 5 Upstream there has been a big change. It's greener with grass and general vegetation. Downstream has improved in greenness but not as much

Kipico

Person 1

- 1) Slightly greener and more abundant vegetation by bed
- 2) Slight increase in vegetation further into banks
- 5) Change has just upstream (no change downstream)

Person 2

- 1) Increased abundance of vegetation by bed and greener
- 2) Further away from bed you have more moisture and an increase in vegetation (further from bed)
- 3) More change has been seen closer to the bed
- 5) Less vegetation downstream (drier) since construction

Ngulai

- 1) Vegetation has changed quite a lot. Increased in abundance, they're not dying like they were before. Has also been an increase in ant hills since construction
- 2) Have changes next to and further away from the bed
- 3) Upstream near the riverbank you have an increase in small trees and further away you have many, more small trees, but not bigger trees. You have more change further away from bed

- 4) Changes are due to water from the dam, with an increase in the water table.
All of the vegetation is natural
- 5) Downstream, the amount of sand has reduced. You have a very small
increase in vegetation downstream

Nthonzweni

- 1) Big change in vegetation: getting greener and more abundant by the
riverbed
- 2) Less increase in greenness further away from the riverbed but still some
change
- 3) More change closer to the bed
- 4) Planting has increased a lot
- 5) Downstream is less green than upstream but downstream is more green
than last year

Wambiti

Person 1

- 1) Has become greener since dam construction.

Person 2

- 1) Little grasses have grown in silt upstream but no other changes in terms of
vegetation density / abundance.
- 2) There has been some change further away from bed: bigger trees have got
greener
- 3) There has been more change closer to the bed
- 4) There has been an increase in food growing close to the dam and also
further away at people's shambas because people can carry the water from
the dam on donkeys to their homes

- 5) Downstream, people are using ponded water and the natural water table has risen, so people are using the water more now to irrigate. Also, trees and Napier have got greener downstream in the bank. There's an increased abundance in vegetation upstream and downstream

Kyakivandi

Person 1

- 1) Far greener now
- 2) There is some change further away from bed
- 3) There is more change closer to the bed
- 4) People are planting kales and bananas now on the immediate banks due to water upstream in the bed availability
- 5) There's a small change downstream. Vegetation is drying up faster in the banks downstream and bed because there's no water downstream now

Appendix L: Interview questions and answers on vegetation along the riverbanks

Appendix M Construction interview

Questions

Interview questions on dam wall construction for construction crew

- 1) How did you decide at which depth to stop chipping away the rock and to construct the wall? (When is the rock deemed solid enough / how did you decide?)
- 2.) Please could you indicate what you think a fracture is and whether you considered that the rock you built onto contained fractures.
- 3.) Once you reached the desired rock, but before construction, did you need to clean out any fractures? If yes, how did you decide they needed cleaning out? Please specify average width and depth which would merit this.
- 4.) Once you reached the desired rock, but before construction, did you need to fill in any fractures? If yes, how did you decide they needed filling in. Please specify average width and fracture and depth filled to.

Interview questions on dam wall construction for team at Africa Sand Dam Foundation (ASDF - NGO)

- 1) How do construction crews know when to stop digging (know how much to chip away) - having reached the material onto which they will construct - how do they know when the rock is unweathered enough?
- 2.) Are construction crews encouraged to clean out and fill in fractures?
- 3.) What do you actually define as a fracture, which require cleaning and filling?

Answers

Nthonzweni (construction crew)

1. Stopped chipping when reached solid rock. On the left hand side, they reach bedrock at approximately 4.3m bgl. They terraced onto a combination of bedrock and sand. In the spillway, bedrock was reached at approximately 4.9m bgl and on the right hand side up to 7.3m bgl. On the right hand side where bedrock wasn't reached, they terraced onto sand. Otherwise, they built onto solid rock.
4. Filled in fractures with cement. Cleaned with brush first.

Wambiti (construction crew)

1. Were guided by artisan in terms of depth. Built onto solid rock. Reached solid rock across whole length of wall. Rock was non-weathered.
3. Fractures: cleaned with wire brush and then filled them with cement using shovel (mason hand tool)

Kyakivandi (construction crew)

1. Hacking in rock removed the top weathered rock to attain a firm foundation of unweathered rock
3. Fractures were minimal, but those that did exist were cleaned before filling
4. The fractures in rock were sealed by the grout cement that seeps from concrete following proper vibration.

Extra info.) Used reinforced concrete for the keyway and the dam wall. Ensured proper anchoring of the dam wall at the wing walls and constructed an apron cast on the dam wall toe. This ensures no water bypasses the wall which may lead to leakages hence failure by the structure. Involved technical experts at each stage and did proper surveys and designs to give a sound structure. For the key wall, recommended excavation is 0.6m by 0.6m along the dam wall axis.

Interview answer on dam wall construction from ASDF for mature sites

1. The digging of the sand dam foundations is supervised by the technical staff. They stop digging once they have hit the firm basement rock from where construction can start. This a rock formation that is not weathering off but hard to dig through
 2. Yes, the construction crew must ensure that the firm rock is cleaned off from all loose rock debris and dirt. Fractures that are found within the foundation of the dam are cleaned as well and filled. The filling is done from an assessment of their nature and possible risk to the sand dam.
 3. Fractures would be defined as cracks on the basement rock within the main dam axis that require attention to ensure that they don't affect the functionality of the sand dam in future. For example, by draining the dam or being a point of weakness with possible undercutting.
- Once the firm basement rock has been found any fractures within the main dam axis are assessed and actions needed to fill them defined.
 - Sometimes the basement rock will also be characterised by main rocks laying on one another and therefore the need to join them by filling.

Appendix M: Interview questions and answers on dam wall construction for construction crew and ASDF

Appendix N Upstream reaches of model

	Site					
Reach	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
1 (m)	0 – 119	0 – 54	0 – 99	0 – 49	0 – 109	0 – 49
2 (m)	119 – 199	54 – 174	99 – 149	49 – 94	109 – 200	49 – 139
3 (m)	199 – 320	174 – 350	149 – 199	94 – 240	200-300	139 – 200
4 (m)	320-420	350-450	199 - 250	240-340		200-300
			250-350			

Appendix N: Upstream reaches that each site is split into (m). Reported in metres upstream of the dam wall. The last reach extends beyond the upstream extent of the trapped sand for 100m.

Appendix O Drainable porosity

Material	Minimum drainage porosity (%)	Maximum drainage porosity (%)	Average drainage porosity (%)	References
Alluvium	7	35	21.8	(Borst & Haas, 2006; Dubreuil, 2017; Hut et al., 2008; Quilis et al., 2009; Quinn et al., 2019; Simon, 2019; Trincheria et al., 2015; Yifru et al., 2021)
Saprolite	1	10	3.9	(Dewandel et al., 2010; Durand et al., 2017; Taylor et al., 2010; Vouillamoz et al., 2014)
Saprock	0.0006	1.7	0.7	(Boisson et al., 2015; Dewandel et al., 2010; Maréchal et al., 2004, 2006; Pacheco & Van der Weijden, 2011)

Appendix O: Absolute minimum and maximum and average values of drainable porosity of alluvium, saprolite, and saprock from literature

Appendix P Model calibration parameters and performance indicators

	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
Calibrated parameters						
Specific yield reach 1	0.35	0.22	0.21	0.35	0.22	0.22
Specific yield reach 2	0.35	0.22	0.07	0.35	0.35	0.22
Specific yield reach 3	0.35	0.22	0.08	0.35	0.07	0.19
Specific yield reach 4	0.35	0.22	0.07	0.35		0.22
K alluvium	0.0005	0.0004	0.0005	0.0005	0.0005	0.0005
K soil	0.0006	0.0006	0.0001	0.0006	0.0006	0.0006
K saprolite	4E-06	6E-06	1E-06	6E-06	6E-06	2E-06
K saprock	1E-07	1E-06	2E-06	2E-06	2E-06	1E-06
Performance indicators						
Squared difference between	0.0002	0.004	0.19	0.002	0.01	0.0007

observed and modelled water levels reach 1						
Squared difference between observed and modelled water levels reach 2	0.03	0.03	0.13	0.01	0.07	0.0007
Squared difference between observed and modelled water levels reach 3	0.06	0.002	0.02	0.01		0.00002
Squared difference between observed and modelled water			0.006			

levels reach 4						
Sum of squared differences	0.09	0.03	0.35	0.03	0.08	0.001

Observed compared to modelled water levels (mbgl) at each site in the short dry season

	Reach 1		Reach 2		Reach 3		Reach 4	
	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
Kithunthi	98.937	98.923	99.064	99.250	99.994	99.753		
Kipico	97.949	97.883	98.222	98.062	98.742	98.786		
Ngulai	98.726	99.165	99.153	99.516	99.476	99.608	99.774	99.850
Nthonzweni	97.610	97.567	97.952	97.831	97.960	97.857		
Wambiti	99.250	99.352	99.078	99.346				
Kyakivandi	99.387	99.413	99.387	99.413	99.84	99.835		

Appendix P: Calibrated values of specific yield and hydraulic conductivity used at each site in the final model, squared difference between the measured and modelled water levels in each reach at each site, and the absolute modelled compared to observed water levels in each reach at each site.

Appendix Q Estimate of evapotranspiration rate

Vegetation type	Crop coefficients (Kc) *
Grassland	0.8
Trees	0.7
Crops (corn - end of season)	0.6
Shrubs	0.5

*<https://www.fao.org/4/X0490E/x0490e0b.htm>

Potential evapotranspiration rate (mm/day) *
4.5

*Quinn et al. (2018)

	% Vegetation cover *					
Vegetation type	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
Grass	35	44	47.5	10.5	11.3	18.8
Trees	2.8	2.8	5.8	15.3	1.3	1.5
Crops	6.8	6.3	0	12.5	4.3	7.5
Shrub / herbaceous	9.5	16.3	16.3	6.8	7.5	12.5
Total vegetation	54	69.3	69.5	45	24.3	40.3
Bare	46	30.7	30.5	55	75.7	59.7

*Calculated from observations at each site

Vegetation type	Actual evapotranspiration rate (mm/day)					
Grass +	0.6					
Trees *	3.2					
Crops +	0.5					
Shrubs +	0.4					
	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
Weighted evapo-transpiration (mm/day)	0.4	0.5	0.6	0.6	0.2	0.3
Weighted evapo-transpiration (m/day)	0.0004	0.0005	0.0006	0.0006	0.0002	0.0003

*Potential evapotranspiration x crop coefficient

+ Potential evapotranspiration x crop coefficient x (soil moisture / field capacity)

Estimated dryland soil moisture of 5% (Nagahage et al, 2019) and field capacity of 27.5% (Gould, 2024)

Area across which evapotranspiration is calculated (m ²) *					
Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
60000	70000	50000	48000	40000	40000

*Based on two riparian zones x the estimated length of accumulated alluvium at each site x estimated maximum width of sand dam influence

Volume of water lost to Evapotranspiration						
	Kithunthi	Kipico	Ngulai	Nthonzweni	Wambiti	Kyakivandi
M ³ /day	22.9	32.5	27.6	30.5	6.5	10.2
M ³ /short dry season	1697.6	2408.2	2041.6	2256.5	480.5	752.3
As a % of lateral seepage	99	89	89	63	9	40
As a % of overall loss	85	85	77	50	6	23

*Evapotranspiration rate (m/day) x area (m²)

Appendix Q: Estimation of evapotranspiration rate at each site using crop coefficients, estimated values of climatic controls, and % coverage of different vegetation types from vegetation surveys

Appendix R Hydraulic conductivity

Material	Minimum hydraulic conductivity values from literature (m/s)	Maximum hydraulic conductivity values from literature (m/s)	Median of mid-range of hydraulic conductivity values from literature (m/s)	References
Residual soil	0.0001	0.001	0.0006	(Brooks, 2009; Ebel et al., 2008; Graham et al., 2010; Graham et al., 1997; Haga et al., 2005; Harr, 1977; Katsuyama et al., 2005; Kosugi et al., 2006)
Alluvium	0.00001	0.0007	0.0004	(Dubreuil, 2017; Hoogmoed et al., 2007; Hut et al., 2008a; Quinn et al., 2019; Strohschein, 2016a)
Saprolite	1E-09	0.0003	3E-06	(Allen, 1989; Bianchi et al., 2020; Chilton & Foster, 1995; Chilton & Carrington, 1984; Dewandel et al., 2006; Graham et al., 1997; Harr, 1977; Hoogmoed et al., 2007; James et al., 2010; Katsuyama et al., 2005; Okogbue & Omonona, 2013; Renken, 1996; Shemang & Jiba, 2005; Strohschein, 2016; Taylor & Howard, 2000; Tijani et al., 2010; Tromp-van Meerveld et al., 2007; Uchida et al.,

				2003; White et al., 2002)
Saprock	1E-08	1E-04	8E-07	Allen, 1989; Borst & Haas, 2006; Caine & Tomusiak, 2003; Chilton & Foster, 1995; Desbarats, 2002; Gleeson et al., 2011; Jeanpert et al., 2019; Kahn et al., 2008; Katsura et al., 2009; Manning & Solomon, 2005; Raj, 2020; Tiedeman, 1998; Voeckler & Allen, 2012; Welch et al., 2012)

Appendix R: Hydraulic conductivity of each material in the weathered basement profile: absolute minimum and maximum, and median of mid-range of hydraulic conductivities in literature

Appendix S Riverbed – riverbank composition

Site	Riverbed – riverbank composition left hand side (m upstream from dam wall)	Riverbed – riverbank composition right hand side (m upstream from dam wall)
Kithunthi	0 – 100: Brown sandy loam	0 – 100: Very loose brown gravelly fine – very coarse sand overlain by silt
Kipico	0 – 3: Gneiss bedrock 3 – 100: Moderately dense reddish black silty fine – very coarse sand underlain by very dense brown sandy silt	0 – 19: Silty red fine sand with outcrops of pegmatite (9 – 11 m). Underlain by very dense brown sandy slightly gravelly silt. 19 – 100: Pegmatite. Up to 57.5 m, rock is underlain by silt
Ngulai	0 – 20: Loose reddish brown and beige fine – medium gravelly sand overlain by rock salt and underlain by silt 20 – 100: Loose reddish brown slightly gravelly fine – medium sand overlain by very sporadic salt rock and underlain by silt	0 – 30: Loose fine – coarse sand overlain by gneiss bedrock (20% cover) and underlain by silt. 30 – 55: Gneiss bedrock in silt, 90% cover 55 – 85: Gneiss bedrock at base up to 30 cm from bed, overlain by beige gravelly fine – coarse sand for 1 m with salt rock, overlain by reddish brown clayey silty sand 85 – 95: Silt with unweathered gneiss dipping, 70% rock coverage 95 – 100: Very soft reddish brown sandy clayey silt with vegetation and clayey loam
Nthonzweni	0 – 20: Moderately soft clay and sand; slightly weathered gneiss bedrock 20 – 100: Moderately stiff brown slightly sandy clay soils	0 – 50: Loose sandy soils underlain by moderately soft clay 50 – 100: Vertical riverbanks composed of moderately soft hard baked sandy clay
Wambiti	0 – 10: Unweathered gneiss	0 – 15: Unweathered gneiss

	<p>10 – 40: No rock, hard baked red medium sand</p> <p>40 – 70: Very loose brown coarse sand underlain by soft brown sandy clay with rock outcrop (5% unweathered gneiss)</p> <p>70 – 100: Very loose coarse brown sand underlain by soft brown sandy clay</p>	<p>15 – 50: Moderately loose, brownish red clayey silty medium sand, underlain by soft brown sandy clay</p> <p>50 – 100: Moderately loose, brownish red clayey silty medium sand, underlain by soft brown sandy clay with sporadic rock outcrops (20% unweathered gneiss)</p>
Kyakivandi	<p>0 – 100: Moderately stiff brown clay overlain by reddish brown coarse sandy loam. No rock</p>	<p>0 – 5: Moderately soft dark brown sandy clay overlain by reddish brown sandy loam</p> <p>5 – 7: Moderately soft dark brown sandy clay overlain by reddish brown sandy loam with unweathered gneiss</p> <p>7 – 100: Reddish brown sandy loam</p>

Appendix S: Riverbed – riverbank composition from the dam wall to 100m upstream on both the left and right hand sides of the riverbed

Appendix T Pool depth

	Kithunthi	Nthonzweni	Wambiti
Depth of original pool (mm)	270	400	220
No. of days elapsed before second depth measurement (days)	28	28	29
Depth of pool at second depth measurement (mm)	180	300	100
Depth pool should be on second date of measurement based on evaporation rate of 6 mm/day and no seepage	102	232	46

Appendix T: Assessment of actual and expected downstream pool depth at Kithunthi, Ngulai, Nthonzweni, and Wambiti in 2023, based on observed pool depth and expected pool depth if only impacted by evaporation at 6 mm/day

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