CLIMATE-SMART IRRIGATION: DEVELOPMENT OF A FRAMEWORK FOR CONJUNCTIVE GROUNDWATER AND SURFACE WATER USE FOR SOLAR-DRIVEN SMALLHOLDER IRRIGATED AGRICULTURE

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND

Africa is vulnerable to climate change due to its dependence on rain-fed agriculture and low adaptation capacity. Climate change will likely increase the frequency of droughts and flooding. Aquifer Storage and Recovery (ASR), the purposeful recharge of the aquifer when there is excess water during wet or flooding periods for subsequent abstraction during dry or drought periods has been used for a long time to bridge the gap in seasonal water availability. Bhungroo Irrigation Technology (BIT) is one of the ASR techniques that has been successfully tested in India and Ghana for increasing water availability in the dry season by recharging the aquifer during the wet season. The approach involves constructing a large underground filter box around the borehole to increase recharge from rainfall or rainwater harvested and channelled through structures to the filter box during the wet season, and irrigation water is later pumped from the same borehole during the dry season. In this study, we innovatively complemented the BIT technology with solar-powered pumping to increase irrigation water access at low energy cost by smallholder farmers, off-grid and grid-connected. Therefore, for this system to be successful, the aquifer hydrogeology should be suitable for storing the recharged water, there should be sources of water that can be recharged and the sites should have enough radiation so that solar-powered systems can be implemented.

AIMS

The overall aim was to develop a framework for sustainable conjunctive use of groundwater and surface water using renewable energy in smallholder irrigation schemes in South Africa. The following were the specific aims of the project:

1. To assess the site suitability of Bhungroo Irrigation Technology (BIT) and solar irrigation pumping for groundwater and surface water conjunctive use in smallholder irrigated agriculture in the Inkomati-Usuthu Water Management Agency (IUCMA) in South Africa

2. To install BIT and solar powered pumps, and develop a methodology to assess the performance of the groundwater and surface water conjunctive system (BIT) using geochemistry and isotopes methods

3. To apply citizen science approaches to monitor conjunctive water use from the bundled BIT and solar irrigation pumping technologies

METHODOLOGY

The Multi-Criteria Decision Making (MCDM) in conjunction with the Geographic Information Systems (GIS) was applied in this study to identify suitable areas for both solar irrigation pumping and BIT implementation at Inkomati-Usuthu Catchment Management Agency scale. The Analytic Hierarchy Process (AHP) method was then applied to assess the influence or weights of individual parameters on the suitability of Bhungroo recharge and solar energy. A set of 10 parameters including land use and land cover, soil type, depth to groundwater, geology, slope, rainfall, drainage density, proximity from the road, population density, and solar irradiation were considered in the analysis. The availability of rainfall, was used as a proxy for runoff water required as a source of water for ASR in the catchment.

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Two study sites, each managed by a female and male farmer were selected in the Inkomati-Usuthu Catchment Agency in South Africa for implementation and performance evaluation of pilot projects of bundled BIT and solar irrigation. The methodology involved the use of results from suitability mapping of BIT and solar irrigation pumping to access suitability of the two sites, and identify source of recharge water, the design and installation of BIT and solar irrigation pumping system, and monitoring of water and energy use, carbon emissions, and the estimation of crop yield and gross margin. At the two sites, as there were existing boreholes, these boreholes were retrofitted with the filter box around them to turn them into BIT. Water quality, chemical and isotopes (oxygen, hydrogen and tritium) before and after installation of the Bhungroo was monitored to evaluate any water quality changes due to the artificial recharged water. The tritium isotope was analysed before Bhungroo installation to evaluate the age of groundwater in the area.

General guidelines were developed to ensure appropriate implementation of this bundled technology (BIT, artificial recharge and solar irrigation pumping) to other dry areas and regions, in such a way as to cause no-harm to both humans and the environment.

Lastly interviews and physical evaluations on technical, biophysical, financial, social, and environmental factors were carried out with different stakeholders to identify opportunities and barriers of solar irrigation adoption in South Africa. The stakeholders interviewed included solar pump companies (suppliers and or installers of solar irrigation systems), policy makers (government ministries and departments), international development agencies (e.g. funders, non-governmental organizations, non-governmental Organizations), academic and research organizations (e.g. universities, and research in organizations), and solar powered irrigation users and user groups (individual, cooperative and group farmers).

RESULTS AND DISCUSSION

The study showed areas with very high suitability for both solar pumping and BIT, accounted for 11% of the analysed land area in the IUCMA (4 241 km^2), area of high suitability (5 166 km^2; 13%), moderate (6 262 km^2; 16%), low (4 503 km^2; 12%), and very low (2 790 km^2; 7%). These areas are located to the west of Barberton town. The result showed that around 40% (15 669 km^2) of the area was available for both technologies with moderate to very high suitable sites. The rest of the area 41% (16 117 km^2) was excluded from suitability mapping as it is restricted, and is under dams, wetlands, conservation and protected areas.

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This study contributed to the suitability assessment of areas that have adequate solar energy and are suitable for surface water and groundwater use from the BIT. Solar photovoltaic (PV) power can replace a significant proportion of the mains electricity and diesel currently used in rural water pumping. Studies such as this are instrumental for improved resource impact assessments in future. Solutions to curb the challenges such as shortage of irrigation water and energy faced by smallholder farmers should go beyond the farm level productivity, to providing an integrated solution along the agricultural value chains (e.g. inputs, outputs, maintenance, etc.) for increased income from crop production.

Water quality analysis prior installation of BIT, showed that all groundwater samples contained detectable amounts of tritium (1.0-1.9 TU) which indicated recharge, indicating presence of recharged water, and suitability of the sites for artificial recharge. The chemical water quality was excellent and way below the irrigation water use standards for South Africa. Groundwater recharge estimates from Chloride Mass Balance (CMB) method appeared to be relatively low and varied from 10-15%, and comparable to estimates from the isotope method that ranged from 6-18% of mean annual precipitation. The recovery rates of recently recharged water from the Bhungroos were 6% and 18% for White River and Schoemansdal, respectively. Bhungroo technology complemented with solar irrigation pumping increased irrigation water availability (6-18%), reduced energy costs (9-42%), resulting in increased farm gross margin (29-84%). Other social benefits from the solar powered pumps include less cost to operate and environmentally friendly compared to fuel and grid connected electric pumps. The complementary technologies owned and operated by farmers provide a promising approach for climate change adaptation and should be promoted and adopted for sustainable groundwater and energy use, and resilience building to dry periods, droughts and climate change in arid areas.

Policy implication from this study include increasing awareness on the performance of combined BIT and solar pumps to encourage adoption by farmers in the pilot sites and beyond. Increase adoption by increasing affordability (e.g. giving farmers a way to cover the initial costs over a longer period) and financial support using different models, such as banks and microfinance institutions may work in partnership with farmer cooperatives to offer credit lines for solar powered irrigation and BIT with appropriate repayment structures. The solar pumps installed were of good quality, designed to match the sites conditions, and professionally installed and there were no operation or technical challenges for the past 2 years. This requires government to implement market protection strategy through certification scheme for solar powered irrigation system suppliers and installers to enhance consumer confidence in solar products and discourage non-qualified suppliers and installers in the market. Like any technology the complementary technology (BIT and solar irrigation pumping) has its own limitation under prolonged drought years, with lots of solar energy and limited runoff in drought years, low groundwater storage, and increasing irrigation demand, this intervention may not be very effective in securing irrigation water supplies.

When the BIT and solar irrigation are deployed, the benefits for farmers include increased crop resilience, improved livelihoods (increased productivity and incomes, and food security), increased social welfare (poverty alleviation, emissions reduction, health), reduced manual work and improved expenditure of time and reduced spending on fossil fuel. For government, the benefits include reduction or savings in electricity and fuel use, subsidy savings, reduced fuel imports, creation of small businesses/employment across the value chain, improved reliability of power systems, increased agricultural economic output, emissions reduction. In an effort to contribute to a number of Sustainable Development Goals, these solutions are becoming increasingly widespread. The BIT and solar irrigation deployment also contributes to a number of Sustainable Development Goals, on hunger, poverty and inequality reduction, gender equality and reduction of carbon emissions, under Climate Action.

Despite these successful results, there is risk of groundwater over abstraction. The use of solar irrigation system may result in excess water withdrawal due to the zero or minimal operational costs nature of the systems, hence there is need to implement the technology bundle with improved irrigation water use efficiency such as more efficient irrigation methods, monitoring water use and groundwater levels and management. For example, changing surface and sprinkler irrigation to drip irrigation. Like any technology the complementary technology (BIT and solar irrigation pumping) has its own limitation under prolonged drought years, with lots of solar energy and limited runoff in drought years, low groundwater storage, and increasing irrigation demand, this intervention may not be very effective in securing irrigation water supplies.

GENERAL

The BIT and solar irrigation technology package or bundle was successful implemented at the two sites. The success was evaluated by increased groundwater storage and recovery for irrigation of crops, use of environmentally friendly solar powered pumps that reduced or eliminated the use of grid electricity and fuel, reduced carbon emissions and production expenses, and increased farm income. There are reported challenges to the wider use of BIT systems including potential contamination to groundwater, but proper siting and effective management of BIT can help reduce them. The evaluation of water quality before and after BIT installation showed that some parameter concentrations decreased and a few slightly increased. However, no water quality parameters were above the DWAF (1996) target irrigation water standards. Suggesting that the BIT is unlikely to negatively impact the crop production and irrigation water quality in the long-term.

This project supported an MSc student, who studied the opportunities and barriers for solar irrigation adoption in South Africa.

CONCLUSIONS

The BIT and solar irrigation technology package or bundle can be successfully implemented by a group or individual farmers in dry areas. The success may be evaluated by increased good quality groundwater storage and recovery for irrigation of crops, use of environmentally friendly solar powered pumps that reduce or eliminate the use of grid-electricity and fuel, reduced production expenses and increased farm income. No water quality issues were noted based on sodium adsorption ratio from the recovered irrigation water from the Bhungroo. The citizen science component through farmer and extension training on data collection, and operation and maintenance, built capacity in the study area. The cost of installing the BIT and solar irrigation pumping may be beyond the reach of many smallholder farmers, hence the need for Agriculture banks and microfinance institutions to work in partnership with farmer cooperatives to offer credit lines for investing in BIT and solar powered irrigation technology bundle.

Policy implications:

- Establish and promote standards for appropriately designing solar irrigation pumping equipment in suitable conditions to increase water access and crop production for smallholder farmers.
- Establish smallholder farmer solar irrigation pumping committees with women as leaders and improving extension and technical services.
- Raise smallholder crop diversification levels and move to high value crops (e.g. tomatoes, cabbages) to mitigate risk of a single crop failure and this should be aligned to market access.
- However, the above policies have their limitations as the farmers need to save money to invest in solar irrigation infrastructure and access to markets to sell their produce at good prices.
- Create awareness of technology and benefits, and provide more training to build capacity of farmers and private sector to install and manage solar powered irrigation. Government can leverage grassroot structures such as extension workers, as well as cooperatives and savings club to deliver information and increase awareness on the benefits of solar irrigation pumping. Given the high cost of awareness and capacity building campaigns, spatial populated rural sites the government and development partners should lead these campaigns.
- Consider significantly reducing the overall cost of the pumps, making them more affordable to farmers by introducing tax exempt and duty exemptions or breaks to solar generation components like solar panels, solar pumps and other modern off-grid energy products. These tax exemptions have been implemented in countries that include in Ethiopia, Uganda, Rwanda, and Zimbabwe. Pay-as-You-Go

models can also be implemented by financing companies to improve access of solar irrigation components by farmers.

- Implement market protection strategy through certification scheme for solar powered irrigation system suppliers and installers to enhance consumer confidence in solar products and exclude non-qualified suppliers and installers in the market.

RECOMMENDATIONS

Areas of further study include:

- Expansion of the evaluation of BIT and solar irrigation pumping performance for better understanding in other provinces, such as the Limpopo Province.
- Assessment of different repayment or business models that include repayments after every harvest and Pay-As-You-Go arrangements to increase affordability of the technology bundle (BIT and solar irrigation) to farmers based on farmer resource typology.
- Develop a database to determine current spatial coverage of solar irrigation and operating status in South Africa to measure the adoption rate.

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ACRONYMS & ABBREVIATIONS

AC	Alternating Current
AHP	Analytic Hierarchy Process
ARAP	Agriculture Policy Action Plan
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
BIT	Bhungroo Irrigation Technology
CA	Conservation Alliance
CAADP	Comprehensive Africa Agriculture Development Plan
CI	Consistency index
CR	Consistency ratio
DC	Direct Current
DEM	Digital Elevation Model
DWAF now DWS	Department of Water and Forestry Affairs now Department of Water and Sanitation
EC	Electrical conductivity
ESMAP	Energy Sector Management Assistance Program
FAO	Food and Agriculture Organization
GHI	Global Horizontal Irradiation
GHG	Greenhouse gas
GIS-MCDA	Geographical Information System – Multi Criteria Decision Analysis
GMWL	Global Meteoric Water Line
IGRAC	International Groundwater Resources Assessment Centre
ISRIC	International Soil Reference and Information Centre
IUCMA	Inkomati-Usuthu Catchment Water Management Area
IWMI	International Water Management Institute
Kg	Kilogram
kWh	kilowatt-hour (kWh)
LADA	Land Degradation Assessment in Drylands
LMWL	Local Meteoric Water Line
MAR	Managed Aquifer Recharge
MCDA-GIS	Multi-Criteria Decision Analysis in Geographic Information System
MPa	Mega Pascal
MPPT	Maximum Power Point Tracker
NDP	National Development Plan
NPK	Nitrogen Phosphorous Potassium
PV	photovoltaic
RCMRD	Regional Centre for Mapping of Resources for Development

RI	Random index
SACAD	South African Conservation Areas Database
SADA	South African Data Archive
SADC	Southern African Development Community
SAPAD	South African Protected Areas Database
SAR	Sodium adsorption ratio
SDGs	Sustainable Development Goals
SOTER	Soil Terrain Database
SPIS	Solar powered irrigation system
SRTM	Shuttle Radar Topography Mission
SSA	Sub-Saharan Africa
SWP	Solar water pumping
TDS	Total dissolved solids
TU	Tritium units
UN	United Nations
UN WWDR	United Nations World Water Development Report
UNFCC	United Nations Framework Convention on Climate Change
Wp	watt-peak
WRC	Water Research Commission

GLOSSARY

Aquifer Storage and Recovery (ASR). The purposeful recharge of the aquifer when there is excess water during wet or flooding periods for subsequent abstraction during dry or drought periods has been used for a long time to bridge the gap in seasonal water availability.

Bhungroo Irrigation Technology (BIT). Falls under a sub-group of Managed Aquifer Recharge (MAR) methods called aquifer storage and recovery (ASR) techniques and was designed to infiltrate excess ‘ponding water’ or floodwater for storage underground and abstracted for irrigation during the dry season.

Borehole yield. Is the sustainable volume of water or discharge that can be abstracted from a borehole without excessive drop in groundwater levels.

Climate-smart agriculture. Technologies that guarantee sustainable increases in productivity and income, increased climate adaptation and reduced greenhouse gas emissions below “business as usual”.

Conjunctive use/ water use. Is the coordinated use of groundwater and surface water resources, in a unified way to minimize adverse effects of using a single source.

Recharge. Is the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone (Freeze and Cherry, 1979).

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

According to the United Nations (2015), agriculture sustains the livelihoods of 40% of the world's population, and most of the future growth in agriculture is likely to come from intensification of farming, with irrigation and energy access, playing a key role (FAO, 2011). Around 56% of global irrigated land requires energy and that number is growing with significant greenhouse gas (GHG) emissions. The GHG emissions and irrigation water use are expected to increase in the near future as 60% more food production will be needed to feed the world's population by the year 2050 (African Development Bank, 2019). Agriculture in Sub-Saharan Africa (SSA) is facing challenges due to natural variability and change of climate, controlling the distribution of water through precipitations, and increasing demand resulting in decreasing freshwater availability for other competing uses (WMO, 2020; IPCC, 2019). Dry-spells continue to threaten agricultural production and food security (Sasson, 2012). To keep up with the demands of producing enough food under climate change, climate-smart agriculture and water-food-energy nexus are being promoted by Comprehensive Africa Agriculture Development Plan (CAADP) (Brock and Wellard, 2014). FAO (2013) defined climate-smart agriculture as technologies that guarantee sustainable increases in productivity and income, increased climate adaptation and reduced GHG emissions below "business as usual". Irrigation avails farmer's land for cultivation throughout the year, depending on the availability of water and energy, significantly improving income.

To support smallholder irrigated agriculture production there is a need to explore alternative water and energy supply options, and how these can be implemented and enhanced for greater productivity. Most of the population in southern Africa relies on groundwater for basic needs, with South Africa having 25% of the population relying on groundwater for water supply. Groundwater resources, although they need energy for pumping, are widespread, and less vulnerable to quality deterioration, evaporation, and droughts than surface water resources.

Irrigation water supply is key to crop production in areas such as the Inkomati-Usuthu Catchment Water Management Agency (IUCMA), South Africa, where rainfall is erratic, groundwater replenishment is low and episodic, and droughts that negatively affect crop production and high pumping costs, are frequent. In these instances, most smallholder farmers use both groundwater and surface water sources. Conjunctive use of groundwater and surface water, and effluent is being adapted in many countries to enhance the irrigation water availability and productivity, food and water security, and achieving sustainable growth (Chadha, 2017). This is due to a realization that in many locations, there is not enough surface water or groundwater available, at the right times to meet water demands (Peltier, 2006). This is due to a realization that in many locations, there is not enough surface water or groundwater available, at the right times and places, to meet water demands (Peltier, 2006; Hay et al., 2012; Aither Pty Ltd, 2018).

However, while the potential to benefit from small-scale irrigation appears significant, it is constrained by access to the energy sources needed to pump water and the limited opportunities for gravity-fed small-scale irrigation systems. Electricity is rarely available to farmers on small, dispersed plots and high fuel costs mean that smallholder farmers cannot rely on diesel or petrol pumps for lifting surface water and shallow groundwater. Solar-powered irrigation pumps offer an inexpensive and effective alternative to electric and fuel-based pumps, enabling farmers to overcome energy-related access and cost constraints to production under irrigation. The technology also reduces greenhouse gas emissions and is, therefore, considered a climate-smart technology. These characteristics make the IUCMA a suitable candidate for the application of conjunctive use and solar irrigation pumping approaches.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To assess the site suitability of Bhungroo Irrigation Technology (BIT) for groundwater and surface water conjunctive use in smallholder irrigated agriculture in the IUCMA in South Africa
2. To assess the site suitability of solar-powered technology for pumping water for conjunctive use of groundwater and surface water in smallholder irrigated agriculture in the case study area
3. To develop a methodology to assess the performance of the groundwater and surface water conjunctive system (BIT) using geochemistry, isotopes and analytical methods
4. To apply citizen science approaches to monitor conjunctive use

1.3 SCOPE AND LIMITATIONS

The study looks at combining the application of an artificial recharge method, (BIT) with solar irrigation in smallholder farming systems in IUCMA in Mpumalanga Province in South Africa. The recharge water considered is surface runoff from rainfall, and no waste water is used. The irrigation systems considered are drip and sprinkler. The results from this project will inform investment policies on smallholder agricultural areas suitable for BIT and solar powered irrigation schemes in the study area and other areas with similar context.

The study looks at combining the application of an artificial recharge method, (BIT) with solar irrigation in smallholder farming systems in Inkomati-Usuthu Catchment Management Agency (IUCMA) in Mpumalanga Province in South Africa. The recharge water considered is surface runoff from rainfall, and no waste water is used. The irrigation systems considered are drip and sprinkler. The results from this project will inform investment policies on smallholder agricultural areas suitable for BIT and solar powered irrigation schemes in the study area and other areas with similar context.

1.4 REPORT STRUCTURE

The report first presents introduction, aims, scope and limitations and report structure of the study in Chapter 1. Chapter 2, presents a brief Literature Review on the importance of solar water pumping and Bhungroo Irrigation Technology (BIT), and the bundling of the two practices in this study. Chapter 3, presents the Research Methods and the general study area of two pilot sites where the BIT coupled with solar irrigation pumping were installed and evaluated. Chapter 4 presents the Results and Discussions, while Chapter 5 presents Conclusions and Recommendations. The application of citizen science cuts across all the objectives as the farmers and extensions were trained on data collection and collected data during the study.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This Chapter presents the literature review on the importance of solar power in irrigation, revolution of solar water pumping, the Bhungroo Irrigation Technology (BIT), a form of Managed Aquifer Recharge (MAR) methods called Aquifer Storage and Recovery (ASR) techniques and the Water, Energy Food nexus.

2.1.1 Importance of solar power

Generating electricity on smallholder farms using solar Photovoltaic (PV) technology is an important step towards increasing the resilience and sustainability of farming. The necessity to provide continuous (year-round) water supply for irrigation, and livestock and the relatively small volumes required for stock watering makes this pumping task well suited to solar PV power. Water can be pumped during the daytime from a borehole, dam or stream into a storage dam or elevated tanks for on-demand supply through gravity to livestock watering troughs or irrigation. On most farms, solar PV can provide cost effective energy needs. There are four main configurations for solar pumping (NSW Farmers, GSES, 2015) that include the solar standalone configuration (solar array provides power to a Direct Current (DC) electric pump via an array and motor control system), solar combined with batteries configuration to provide power at night or during low solar energy periods, solar combined with diesel generation configuration, and solar combined with power from the electricity grid configuration to reduce the amount of grid electricity required.

The advantages and disadvantages of solar water pumping are shown in Box 2.1. Some of the advantages and disadvantages of solar water pumping are provided in section (NSW Farmers, GSES, 2015). The advantages and disadvantages of solar water pumping are shown in Box 2.1. A typical solar powered pumping system contains the following equipment: a solar array, which converts sunlight or solar radiation into electricity; system controllers, which control the array and the pump; an electric motor, which drives the pump; and a water pump, which moves the water from a source to point of delivery, which can be a field or a livestock watering trough (Figure 2.1). Solar radiation is amount of energy received from the sun at a given location. This determines how much power each solar module will generate in a day and the size of array needed to pump a required volume of water. A site with low solar radiation levels will need a larger array than a site with high solar radiation levels.

Box 2.1: Advantages and disadvantages of solar water pumping (NSW Farmers, GSES, 2015; World Bank, 2018)

Advantages

- Solar water pumping (SWP) systems consume little to no fuel, thereby reducing bills for mains electricity and diesel. By using freely available sunlight, they avoid the constraints of unreliable or expensive rural fuel supply networks.
- Reduced connection and infrastructure costs when new power lines and poles can be avoided if fully replacing mains electricity.
- Flexible – solar power can be integrated with mains electricity supply or diesel energy if desired.
- Unlike diesel-based systems (i.e. where a diesel generator powers the pump), solar pumping produces clean energy with zero or much reduced exhaust gases and pollutants, and no noise.

- Solar pumping systems are durable and reliable. PV panels have a design life of over 20 years, while solar pumps design life is 10-15 years, and have few moving parts that require little maintenance (unlike diesel pumps), which consists primarily of cleaning the panels when they become dusty
- Solar PV is scalable. Solar pumping systems are modular so can be tailored to current power needs and easily expanded by adding PV panels and accessories.
- Properly installed solar systems are safe and low risk due to low system voltage. Adequate protection minimises fire risk.

Disadvantages

- Solar water pumping systems have high initial capital costs, which can be discouraging. Despite the decreasing cost of solar systems over the past decade due to a drop in the per unit cost of photovoltaic (PV) cells, they continue to represent a significant capital investment for smallholder farmers, with the cost of the cheapest system being twice the average annual income from smallholder farming of US$1 500. However, as component prices are dropping substantially over the past decade, investment payback is quick, and pay-as-you-go financing models are becoming common.
- Water tank storage is preferable to batteries, but still expensive. Hybrid solar/diesel pumping reduce costs by reducing the need for storage.
- Solar pumps still require some servicing, and trained technicians may be difficult to access in some areas. This is gradually improving as more companies are selling solar water pumps (SWP) and providing backup maintenance support. The operation and maintenance can vary depending on the system's complexity.
- Solar panel theft. This can be reduced by community awareness campaigns and providing simple antitheft measures.
- SWP can lead to excessive groundwater abstraction by farmers because of reduced or near zero marginal-cost of pumping groundwater.

2.2 THE REVOLUTION OF SOLAR WATER PUMPING

Over last decade, the technology and price of solar water pumping have evolved significantly and this has increased the individual, cooperatives and companies' appetite for solar water pumping. Firstly, SWP system capacity and ability have expanded. Early solar water pumps had limited performance and were restricted to pumping installations with a shallow water source and a low water demand. Recently, pumps can reach deeper wells, up to 500 meters (m), compared to the previous depth of 200 m, and pump larger volumes of water (1 500 m^3/day, compared to the previous 500 m^3/day at low head (World Bank., 2018). Pump efficiencies have also increased considerably; with new pump and motor designs having increased water volume outputs over the entire pump range.

Secondly, prices of photovoltaic (PV) panels have dropped exponentially. High demand for PV modules for grid-tied applications has resulted in massive economies of scale in production as well as competition among vendors. The price of silicon, a key material in manufacture of PV, has also dropped substantially (World Bank, 2018). Solar modules once costed around $5/Wp (watt-peak); now, they are less than $0.75/Wp (ex-factory) (World Bank, 2018). These cost reductions have made larger SWP systems possible where previously the capital costs were prohibitive. There are also several SWP manufacturers and suppliers, giving customers lot of options to choose from now compared to last decade.

Thirdly, SWP is being mainstreamed and awareness is growing to ensure appropriate systems suited to farm conditions are selected and implemented by farmers. The markets are already demanding SWP in place of conventional pumping solutions, such as fossil fuel (e.g. diesel) and local power grid-based pumps. Diesel pumps are slightly more efficient than alternating current (AC) powered pumps as they allow greater flexibility (Roblin, 2016), but require expensive fuel availability and have greater impact on the environment. In rural areas, especially in developing countries, the access to the electricity grid is unreliable, thus use of an independent and alternative solar energy system can be a solution for the farmer to secure a dependable power source and to reduce pressure on the public grid.

2.3 BHUNGROO IRRIGATION TECHNOLOGY

The BIT (Figure 2.1) falls under a sub-group of Managed Aquifer Recharge (MAR) methods called aquifer storage and recovery (ASR) techniques (Pyne, 1995). The BIT was successfully applied by smallholder farmers in Gujarat state in Western India, and northern Ghana, to store and supply sufficient irrigation water during the dry season, resulting in increased crop production and water productivity (Conservation Alliance, 2015). The BIT is designed to infiltrate excess ‘ponding water’ or floodwater for storage underground and abstracted for irrigation during the dry season (Owusu et al., 2017b). In this study the source of water is surface runoff from the road and area upslope the BIT.

The infiltration pit performs the filtration process through a constructed filtration bed to remove unwanted constituents before transmitting water to unsaturated aquifers for storage. Water is stored in the underlying aquifer during wet season and accessed through pumping using the same borehole for irrigation of crops during the dry season. Some of the limitations of the approach include contamination of aquifer by recharged water and low recovery rates of the recharged water. To complement this BIT, solar-powered pumps are included for pumping irrigation water from the Bhungroo borehole (Figure 2.2)**,** to further enhance resilience to climate change. The combined technology package is referred here as BIT, with solar irrigation pumping.

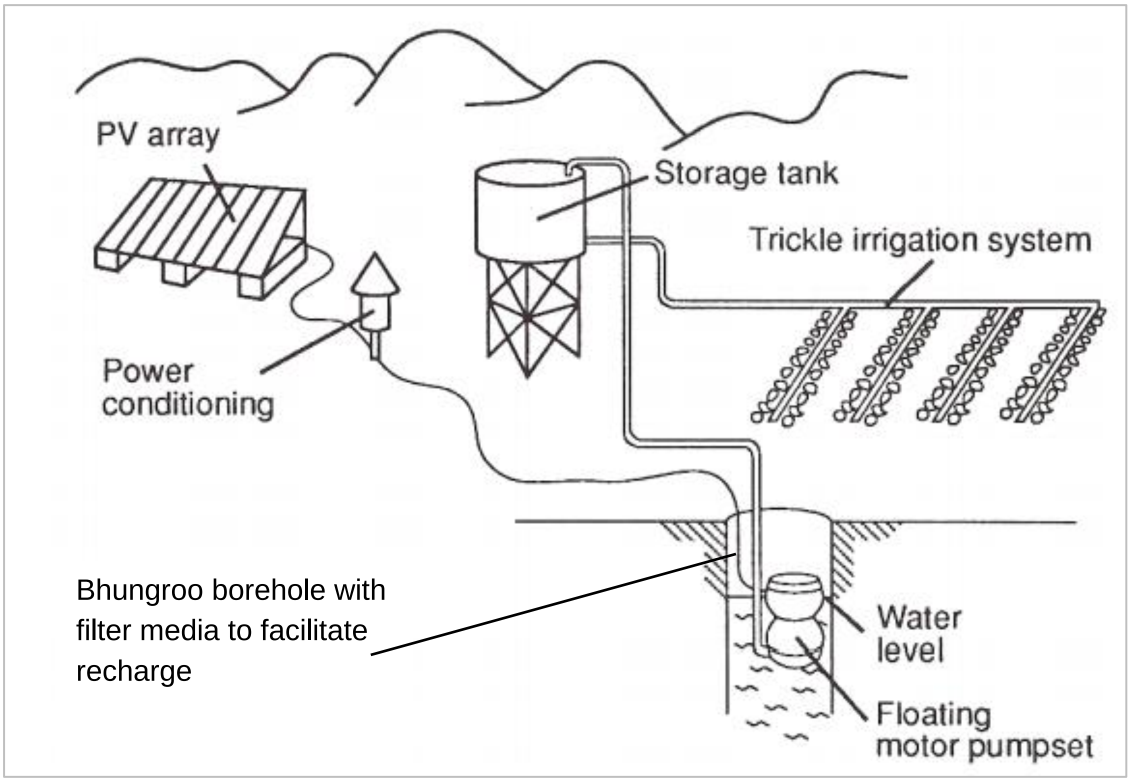


Figure 2.1. Solar water pumping irrigation system (partly adapted from Practical Action, 2012)

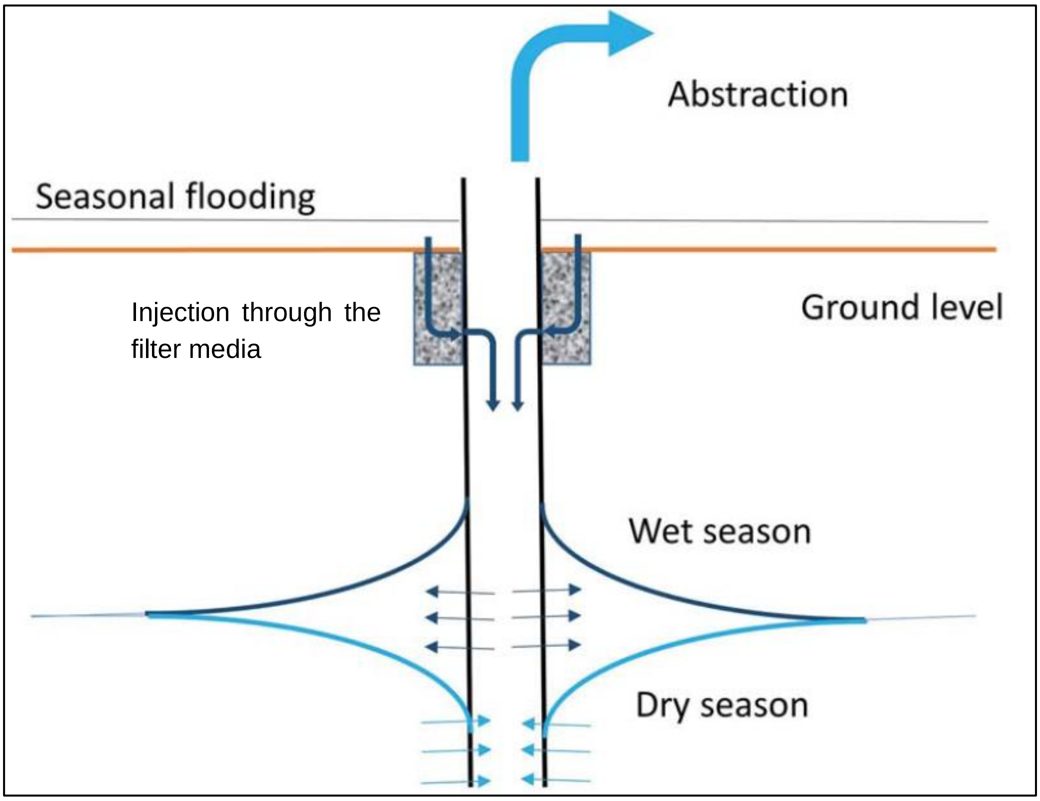


Figure 2.2. Bhungroo Irrigation Technology principles of water infiltration through a filter media and abstraction (Owusu et al., 2017b). Since ASR uses injection wells, the level the water rises to form a cone shape within the vicinity of water in the borehole.

2.4 SOLAR WATER PUMP IRRIGATION – WATER-ENERGY-FOOD NEXUS

To expand the understanding of future trends in the adoption of solar water pump systems there is need to analyse the impact of complex feedbacks in dynamic systems, such as agricultural processes and groundwater management (Green et al., 2020). Agriculture can be considered a coupled social-environmental system, where farmers rely on environmental inputs namely, water, but also seeds, fertiliser and sunshine, and public policies that determine access to these inputs (e.g. capital in the form of pumps) and market conditions that govern how much income can be made. Feedbacks within this system are abundant: poor rains in one year may serve to increase government support to farmers in the next year; subsidies and tax cuts for new irrigation pumps may lead to increased cultivated land; cash incentives for farmers to use efficient amounts of irrigation water for crops can reduce groundwater over-extraction. Hence, the sustainable production of food and water management should include energy access and management, and environmental protection.

CHAPTER 3: RESEARCH METHODS

3.1 INTRODUCTION

This Chapter provides an overview of the of the study area and the research methods applied in the report.

3.2 STUDY AREA

The study area is in the Inkomati-Usuthu Catchment Management Agency (IUCMA), which is located in both South Africa and Swaziland. The IUCMA is situated in the north-eastern part of South Africa in the Mpumalanga Province, with a small area in the Limpopo Province, borders on Mozambique in the east and on Swaziland in the south-east. The water management area extends over several parallel river catchments which all drain in a general easterly direction, and flow together at the border with Mozambique or within Mozambique, to form the Inkomati River which discharges into the Indian Ocean immediately north of Maputo. However, this study only considered part of the catchment in South Africa as shown Figure 3.1.

The IUCMA consists of four sub-catchments, Sabie/Sand, Usuthu, Crocodile, and Komati, with total area of about 37 200 km^2. The IUCMA is water-scarce, as most of the available freshwater resources have been allocated (Denby et al., 2016). The average annual temperature is approximately 20˚C, and the mean annual rainfall ranges from 400 mm/a to 1 500 mm/a. Annual potential evapotranspiration ranges from 1 400 to 2 335 mm/a. The rainfall is seasonal and occurs during the summer season (October to March). The elevation varies from 24 m to 2 277 m above sea level. Vegetation is predominantly open woodland. Irrigated agriculture consisting of crop and fruit trees from both commercial and smallholder farming areas is dominant compared to rainfed agriculture. Two main geological formations exist in the area, the basement crystalline rocks (Precambrian) and the Paleozoic sedimentary rocks. Groundwater availability in these two main geological environments is highly variable due to the weathering process, fractures, and structural lineaments that influence the groundwater flow and storage capacity of rocks.

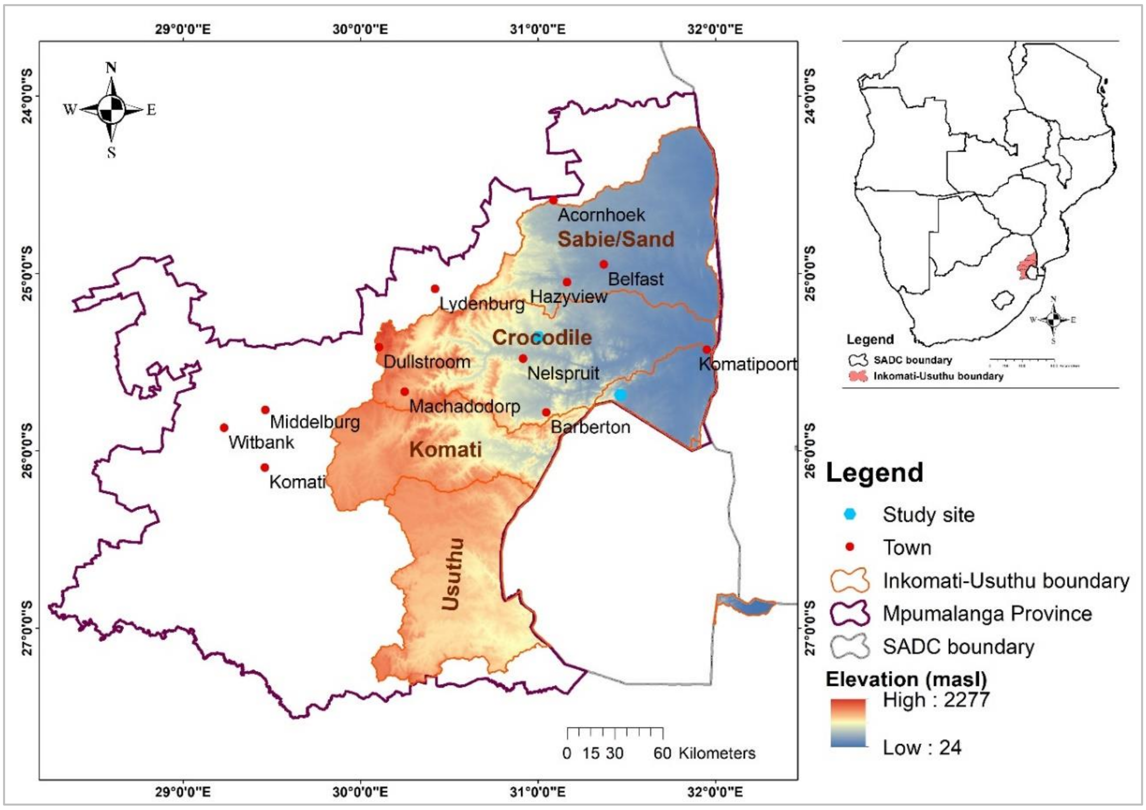


Figure 3.1. Location map of study sites and elevation in Inkomati-Usuthu Catchment Management Agency

The Photovoltaic Electricity Potential of the two study sites in White River farm and Schoemansdal (locally known as Nkomazi) is shown in Figure 3.2. The sites are located in Ehlanzeni District, Mpumalanga, South Africa. The Schoemansdal site is at Ngugwane Co-operative farm and is at a lower elevation compared to White River farm at Sisendleleni Cooperative (Figure 3.1). In White River, the average annual rainfall is 458 mm, with an average of 140.6 rainy days. Schoemansdal is slightly wetter with an average annual rainfall of 488 mm, with 138.5 rainy days (Weather Atlas, 2022). The White River and Schoemansdal sites are located within mafic and extrusives, and compact sedimentary geology, respectively (Figure 3.3). Groundwater availability in these two main environments is highly variable due to the weathering process, fractures, and structural lineaments that influence the groundwater flow and storage capacity of rocks. Brief description of the sites is presented next.

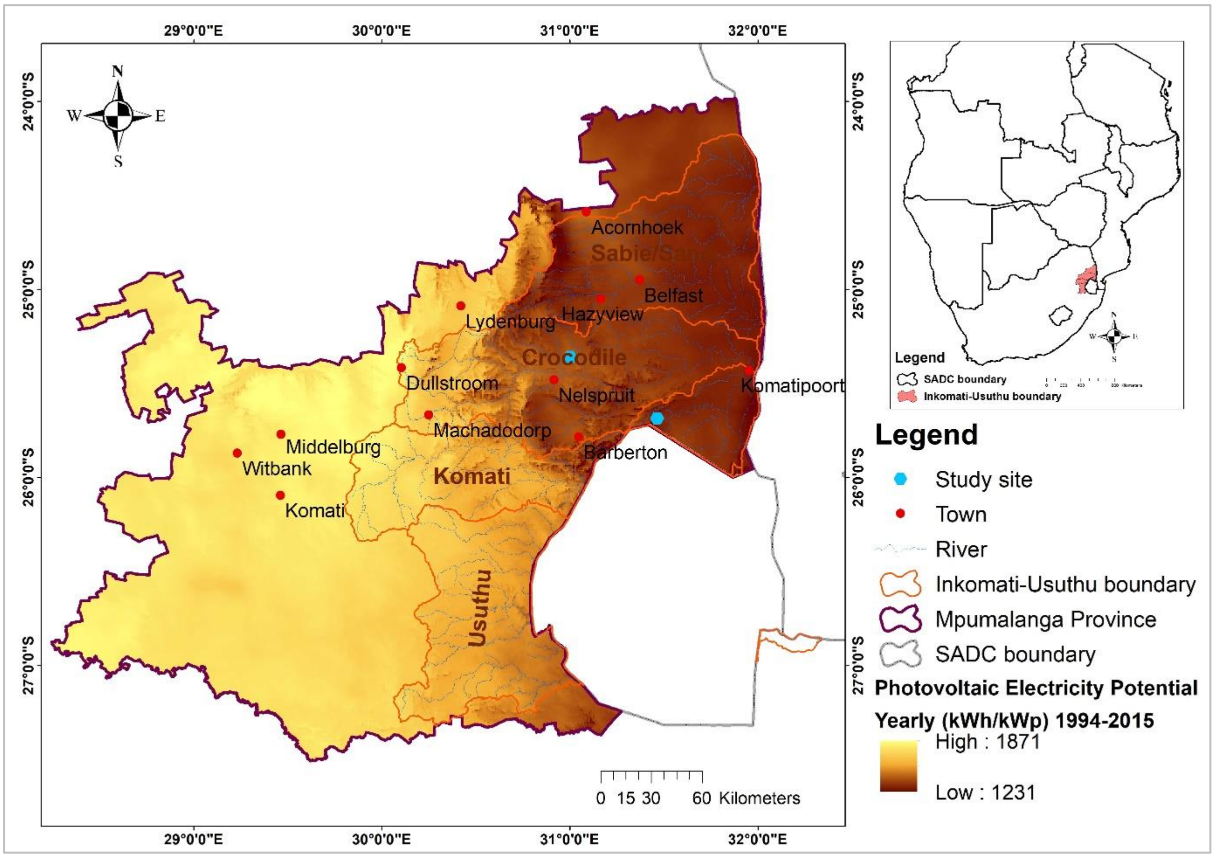


Figure 3.2. Location map of study sites and solar potential in Inkomati-Usuthu Catchment Management Agency (World Bank, 2020).

3.2.1 White River farm

The farm is owned by a cooperative and managed by youth male farmer. The site is not prone to flooding, hence, the modification was made to harvest water from the sloping land area upstream the Bhungroo and channel it to the Bhungroo filter box, as the natural slope was steep and did not allow natural ponding of water around the Bhungroo. Sand traps were constructed in the channel to reduce sediments before the water reaches the Bhungroo filter box (Figure 3.4). The farm area is 5 ha. There are two boreholes (White River BH1 and White River BH2) that are in use at this farm, with a third one (White River BH3) that was drilled but not equipped. White River BH1 is 41 m deep, with static water level of 23 m, while White River BH2 is 35 m depth, with static water level of 4.8 m, and is near a seasonal stream. The borehole yield tests by AGRIENG (2020) recommended abstraction rates of 2.9 ℓ/s (125 280 ℓ/day) for 12 hours pumping and 8 ℓ/s (518 400 ℓ/day) for 18 hours pumping for White River BH1 and White River BH2, respectively. The White River BH1 was selected to implement the Bhungroo technology because of its lower yield and lower groundwater depth, which provides space for the artificial recharge, compared to White River BH2. The White River BH1, mainly supplies a macadamia nut tree nursery. The water is first pumped into a tank and then flows to irrigate the nursery by gravity. The crops monitored in this study were green beans and cabbage. During the first visit to the farm the farmer complained of high electricity bill for irrigation, which was around R9 000/month, and low groundwater levels.

3.2.1.1 Solar pump installation

A 0.75 kW solar pump (MultiFlow Pen 120 Hybrid AC/DC Water Pump), with a maximum pumping head of 60 m and powered by 4 panels (Canadian Solar 345 W Super High Power Poly PERC HiKU) was installed at a depth of 36 m below the ground surface. The solar pump, 4 panels and accessories costed US$ 2 357, with installation and roof brackets costing of US$ 900 (total cost U$ 3 257), while the BIT costed US$1 000 (no casing was required as the ground was stable), based on the exchange rate of US$1= R17.50 (2021).

3.2.2 Schoemansdal farm

The site is owned by Ngugwane Co-operative Farm, and managed by a female farmer. The site is not flooded, hence, the modification was made to harvest water from the sloping road to the Bhungroo filter box, as the slope was steep and did not allow natural ponding of water around the Bhungroo. The Bhungroo borehole (Schoemansdal BH) is 89 m deep and the static water levels was 16 m from the ground surface. No yield test was done for this borehole, but the blow yield observed during the cleaning exercise prior to installation of PVC casing was 0.17 ℓ/s (4 800 ℓ/day). This is low yield, requiring the farmer to benefit more from the artificial recharge from the Bhungroo technology. On average the borehole pumps water for 8 hours per day. The construction of the Bhungroo was done by the project on an existing borehole, and there were challenges of the borehole collapsing due to unstable geology formation. This challenge necessitated the PVC casing of the borehole for the full 89 m depth. The soil type is clay loamy. The farm area of 13 ha is divided into different blocks, from block A to H. Block A is 1.6 ha, B is 0.9 ha, C is 0.7 ha, D is 0.7 ha, E is 0.9 ha, F is 0.25 ha, G is 1.2 ha and H is 6.75 ha. The crops grown include cabbage, green pepper, egg plant, chili, spinach, green beans, maize and sweet potato. Block G is normally for rainfed tobacco. The crops monitored in this study were green beans and cabbage. During the first field visit the farmer raised the challenge of lack of water and low pressure of water in the field, resulting in taking 2 days (each day pumping for 10 hours) to irrigate about 0.5 ha of cabbage. These challenges were attributed to undersized borehole pump and small petrol pump to pump water from the farm dam.

3.2.2.1 Solar pump installation

A 1.8 kW solar pump (Lorentz Submersible PS2-1800 HR14H Pump), with a maximum pumping head of 75 m and powered by 4 panels was installed at a depth of 74 m below the ground surface. The solar pump costed US$ 6 800, while the BIT costed US$ 2 600. The high cost of the BIT was due to the need to clean the borehole and install PVC casing to avoid collapsing of the geology formation.

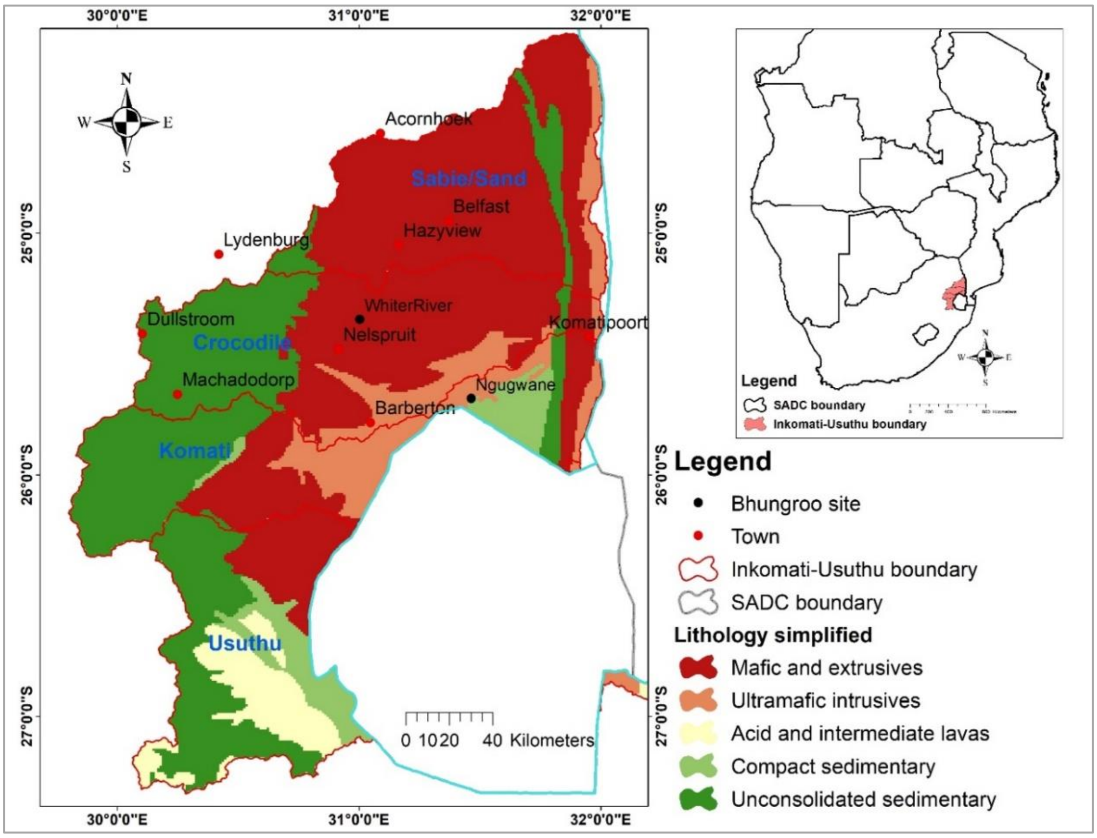


Figure 3.3. Simplified lithology in the Inkomati-Usuthu Catchment Management Agency

Figure 3.4. Channel harvesting runoff to the Bhungroo filter box at White River site

3.3 METHODS

This section provides an overview of the methodologies used in this study. The aim of the methodologies is to establish suitability mapping for BIT and solar irrigation pumping, and assess the contribution from the BIT and solar irrigation pumping towards groundwater recharge and irrigation water availability for crop production. In addition, the methodology investigated the performance of the BIT in terms of recovery rates of water that recharged or infiltrated in to the Bhungroo borehole through the filter material.

3.3.1 Suitability mapping for MAR injection methods in the form of Bhungroo Irrigation Technology

The creation of MAR suitability maps promotes the successful application of MAR. Several studies have assessed the suitability of specific areas for MAR projects using a Multi-Criteria Decision Analysis in Geographic Information System software programs (GIS-MCDA). In this process, a decision maker evaluates alternatives combining different decision criteria information to find the best solution to a specific problem. For MAR, the interest is usually to guide decision-makers to determine the most suitable sites for the successful implementation of a successful MAR application. Research on MAR suitability gained more focus in the past 20 years, with the contribution of research institutes such as IGRAC and Acacia Water, for projects in Kenya and Botswana, and INOWAS (Technische Universität Dresden) for studies in Costa Rica and the Iberian Peninsula.

Although every study used GIS-MCDA to assess ‘MAR suitability’, each of them is made unique by the method used, including the selection of criteria (nature and number), how they were translated into MAR suitability and what weights were given to each of them. This diversity, although necessary to produce suitability maps that are adapted to specific needs and constraints of the study area, makes the approach complicated. Based on experiences from India (Paul, 2013; Naireeta Services, 2015) and Ghana (Owusu et al., 2017a), the essential requirements considered for suitability of BIT included surface, subsurface and socio-economic conditions (Murray 2008; Bunsen and Rathod 2016). The surface requirement included biophysical features such as land-use/land cover type, soil type, surface hydrology and slope of the terrain, as well as support agricultural activities, while the subsurface requirements focused on storage capabilities of the aquifer and included depth to groundwater, and geology. The socio-economic conditions included proximity to the roads for access to the market and population density.

Each criterion was reclassified into appropriate five classes in GIS environment mostly using Jenks Natural Breaks or natural groupings inherent in the data (de Smith et al., 2015). The classes were then standardised using a common scale of 1-5 (where 1 = very low suitability, 2 = low suitability, 3 = medium /moderate suitability, 4 = high suitability and 5 = very high suitability). Standardization by reclassification helped to convert each criterion map to a uniform measurement scale for easy comparison and overlay analysis (Yalew et al., 2016).

3.3.1.1 Surface criteria

The surface factors assessed were landcover, slope, soil and surface water accumulation. Description of each of the factors is presented in the subsections that follow.

Land cover

The land cover has an influence on surface runoff and gives information on the availability of land for implementation of MAR in BIT sites. The land use data with a 20 m resolution was obtained from South African Land cover (2018). The land use was reclassified with respect to the dominant land cover features in the study area. Grassland was ranked 5, due to very high infiltration rates, while cultivated area covering 30% of the total area was ranked 3 (medium infiltration) as reported by Yimer et al. (2008). Natural land cover classes were most preferred sites, due to high infiltration rates, and less runoff generation. Bare ground and degraded vegetation was ranked very low, value of “1” because of high runoff and sediment loads generated from this landcover. Yimer et al. (2008) argued that the changes in soil structure caused by surface soil compaction because of tillage, together with little soil organic carbon content, causes the decline in infiltration capacity and soil moisture content when forest is converted to cultivation and grazing land. Cultivated land had higher infiltration rate than grazing land, but lower than thicket bush and woodlands.

Waterbodies (lakes, reservoirs), conservation (e.g. wetlands) and protected areas (i.e. national forests) were clipped out as restricted layer and had no influence on the overall analysis (Figure 3.5; Table 3.1). Additional data on restricted areas included, conservation and protected areas (e.g. wetlands) was obtained from the South African Protected Areas Database (SAPAD), and South African Conservation Areas Database (SACAD), bare rock and water bodies (South African Land cover, 2018).

Soil type

Soil texture gives indications on the amount of water that can infiltrate through the unsaturated zone to reach the aquifer. Soils with larger particle size will be the most suitable for surface infiltration as the infiltration rate increases with the particle size (Hillel, 1998). The soil data was obtained from ISRIC (International Soil Reference and Information Centre) report on Soil and Terrain (SOTER) database at scale 1:1 million (Dijkshoorn et al., 2008). This database used GIS based methodology to discriminate on calculated pixel values of raster cells of the 90m resolution DEM. This soil was reclassified and ranked based on the capacity to retain water and susceptibility to flooding, as shown in Figure 3.6 and Table 3.1. Soil ranking and standardization were based on soil texture and the associated infiltration capacity (Hillel, 1998) of the soil (Table 3.2). Clay-loam soil was ranked 1, least suitable soil type because of the low infiltration rate (Balana et al. 2015). Soils with very fine texture were ranked unsuitable as they have low infiltration rates. In cases of different texture between topsoil and subsoil, the finest soil texture was selected as it is a limiting factor to water infiltration. Soil thickness also plays an important role, but it is associated with lower data availability.

Slope

Slope is an important factor that controls runoff potential (Selvam et al., 2014; Magesh et al., 2012). A gentle slope reduces the speed of runoff and allows for more time for infiltration compared to a steep slope. Slope was analysed using the 30m-resolution Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) obtained from RCMRD (2020). The slope map showed that northern IUCMA is a generally fat, with 80.9% of the area having average slope of 0-15° (Figure 3.7; Table 3.3). A rank of 5, for most MAR suitable areas was assigned to a slope range of 0-1° which formed 63.9% of the area, while slope steeper than 10° was less suitable and ranked 1.

Drainage density

Reflects the slope and permeability of soils, with steep slopes and low permeability soils typically resulting in a high drainage density not favourable to infiltration but also increasing MAR suitability as there is more surface water available for recharge. The probability of flooding from upstream was used as an indicator of susceptibility of the study area to flooding. A flow accumulation network was developed from the 30m-resolution DEM from SRTM, whereby the flow for each pixel was computed and the upstream accumulation was determined (Jenson and Domingue, 1988). The resulting raster layer provided information on areas with high or low probability of flooding (Figure 3.8; Table 3.3). The high probability areas (>1 000 km^2 threshold) are mainly the river channels which were marked as less suitable due to problems associated with using water directly from the floodplains, while the highest rank (5) was for the range of 100-1000 km^2 for most preferable areas (Owusu et al., 2017b).

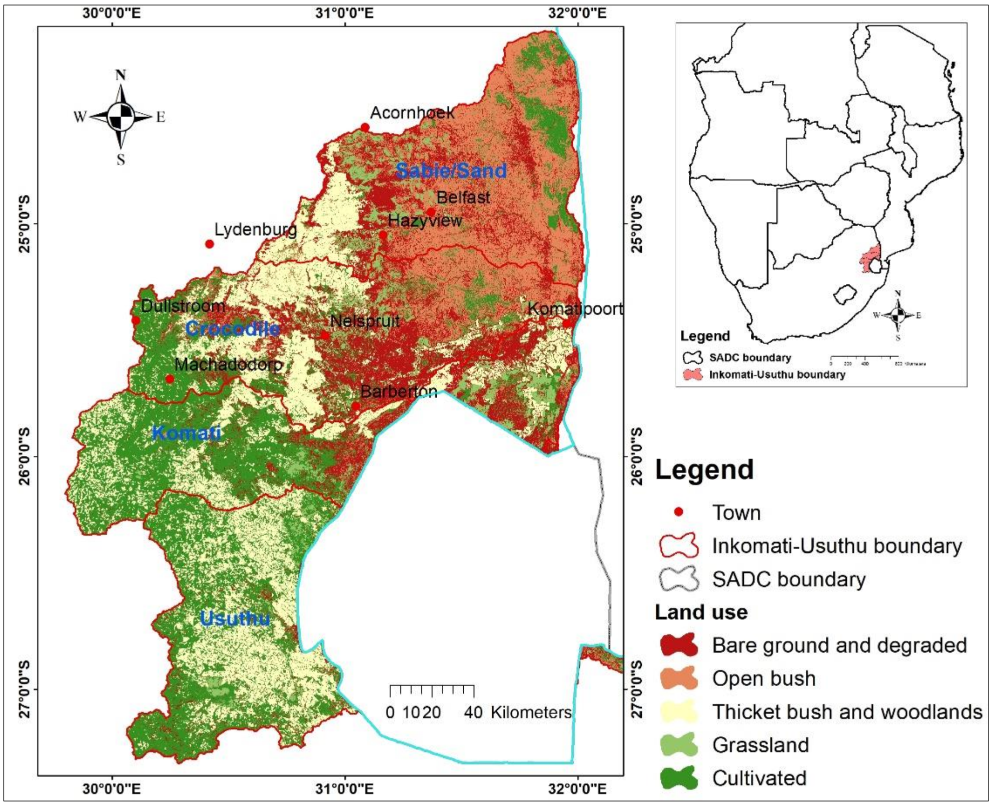


Figure 3.5. Reclassified surface criteria: Land cover in the Inkomati-Usuthu Catchment Management Agency

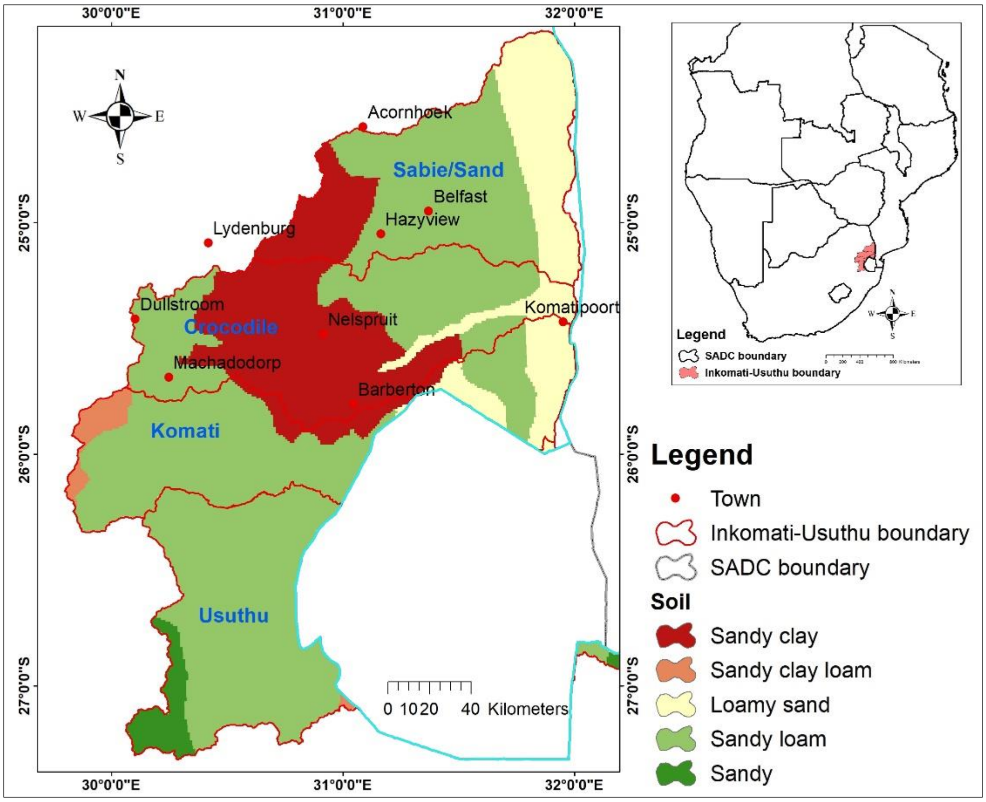


Figure 3.6. Reclassified surface criteria: Soil type in the Inkomati-Usuthu Catchment Management Agency

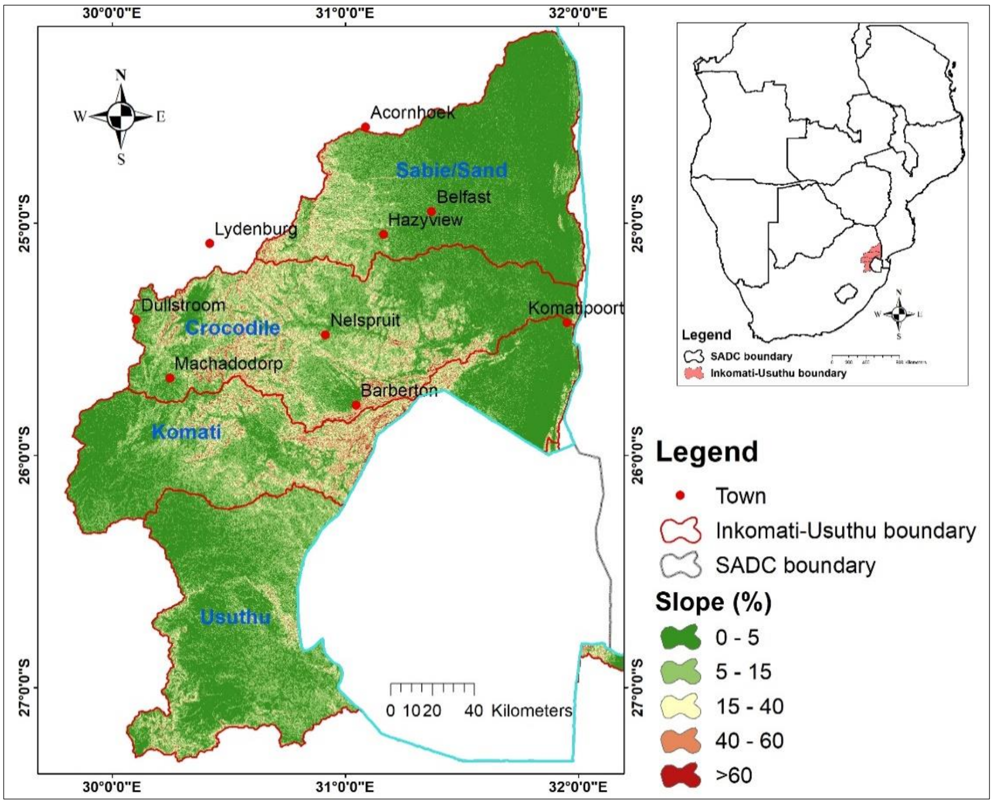


Figure 3.7. Reclassified surface criteria: Slope in the Inkomati-Usuthu Catchment Management Agency

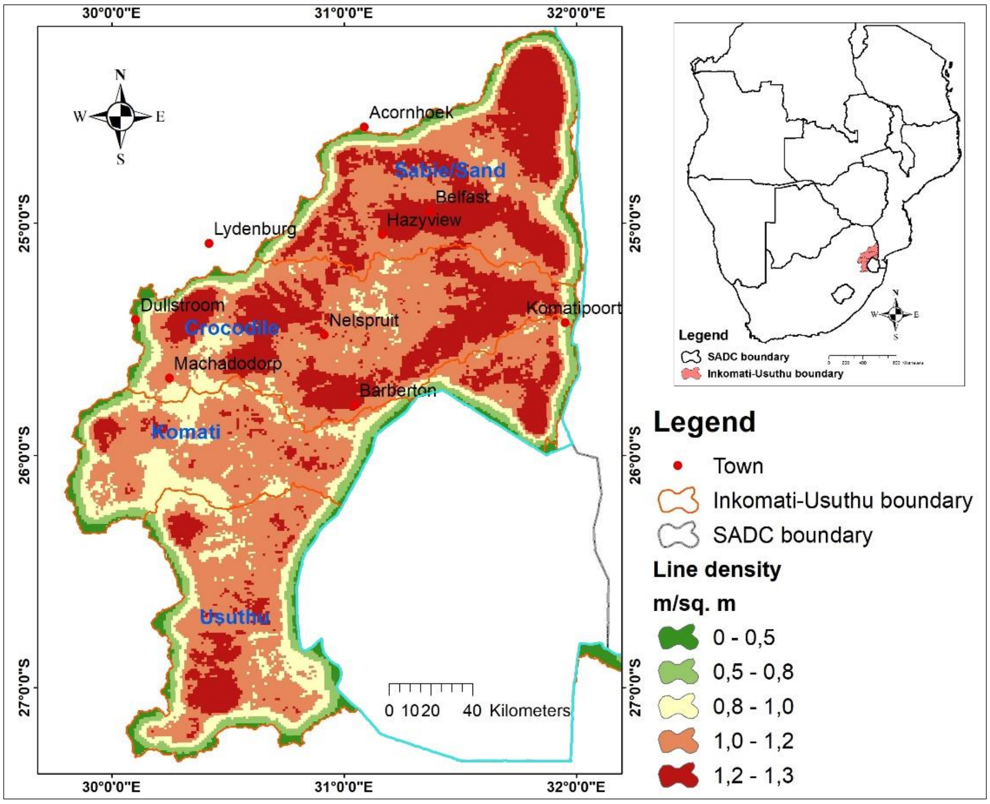


Figure 3.8. Reclassified surface criteria: Line density or drainage density in the Inkomati-Usuthu Catchment Management Agency

3.3.1.2 Subsurface criteria

Subsurface criteria determine the underground storage capacity, which is the ability to store water underground as a function of the hydraulic conductivity and the continuity (fractures, karst) of the aquifer medium. The underground aquifer should consist of a medium, which has good storage, both in terms of the porosity and thickness of the formation (Murray, 2008). The geological indicators of lithology were derived from geological maps developed by Council of Geoscience (2013). Maps containing data on the hydrogeology (depth to water table, recharge) were obtained from SADC-GMI (2018).

Lithology

Lithology descriptions were used to classify geologic units in terms of whether they corresponded to aquifers, or if fine-grained sediment (clay and silt) would likely reduce direct connection to underlying aquifer. Lithology descriptions were used to classify geologic units in terms of whether they corresponded to aquifers, or if fine-grained sediment (clay and silt) would be likely to reduce direct connection to underlying aquifer. Rock type exposed at the surface is an important factor in recharge, percolation of water, and groundwater distribution (Russo et al., 2014; Shaban et al., 2006). Understanding hydrogeologic properties is paramount to predicting ASR suitability. Estimating hydraulic load on an aquifer system from injection wells is dependent upon many of the aquifer's properties, including transmissivity, regional gradient, and geometry (Russo et al., 2014). The geology layer from SA (2016) geodatabase was used to identify lithological formations within the study area. Lithological classes not suitable for MAR were ranked low (e.g. 1), while alluvial formations were ranked high (e.g. 5) as shown in Figure 3.9; Table 3.1.

Depth to groundwater level

Storing water deep underground minimises evaporation, compared to surface storages. The depth to groundwater should be provides enough space for the recharge water to occupy. Shallow groundwater level is less favourable than deep groundwater levels. Depth to the static water level is a controlling factor used to identify potential groundwater rise (Smith and Pollock, 2012). A range of 30-70 m depth of borehole is most suitable for the ASR technique (UNFCCC, 2014). Static water level ranged from 0 to 7.5 m to >100 m, with majority of the area having static water levels from 7.5 to 50 m, which implies high potential for the study area. This layer was reclassified (very shallow, shallow, shallow to medium and medium) to a scale from 1 to 5, with 5 being the most suitable (Figure 3.10; Table 3.1). BIT system requires energy to lift water from the aquifer to the fields, and the deeper the aquifer the more energy is required. Water-lifting technologies that can be used with the BIT system include solar, motorized, electric and manual pumps, and for solar, depths up to 30-40 m are most suitable. The need to balance depth to groundwater and capability of solar pumping results in a non-linear reclassification, because enough storage is required, but the water depth to pump from should not be too deep to avoid huge solar pump investment costs.

Recharge rates

Recharge rates from observational studies were used to identify areas with different recharge rates. Areas with high recharge rates were more suitable for BIT than those areas with low recharge rates. Thematic layers were reclassified to a scale from 1 to 5, with 5 being the most suitable for enhanced recharge. However, this data was not used in the analysis due to the course resolution as the whole catchment had the same recharge (Figure 3.11).

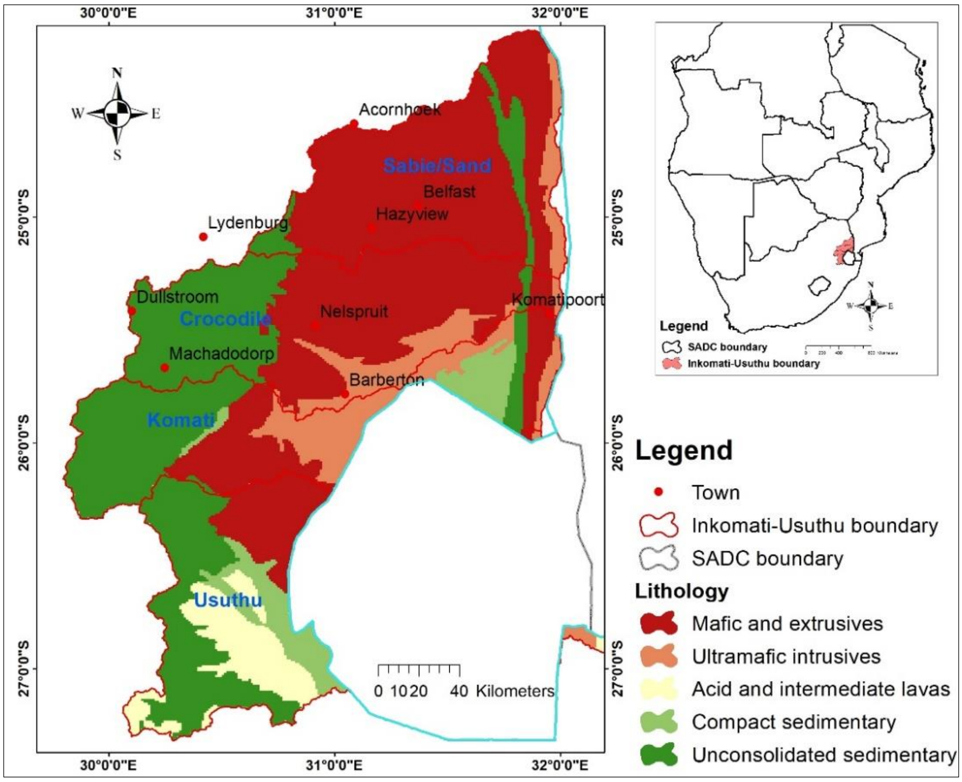


Figure 3.9. Reclassified surface criteria: Lithology in the Inkomati-Usuthu Catchment Management Agency

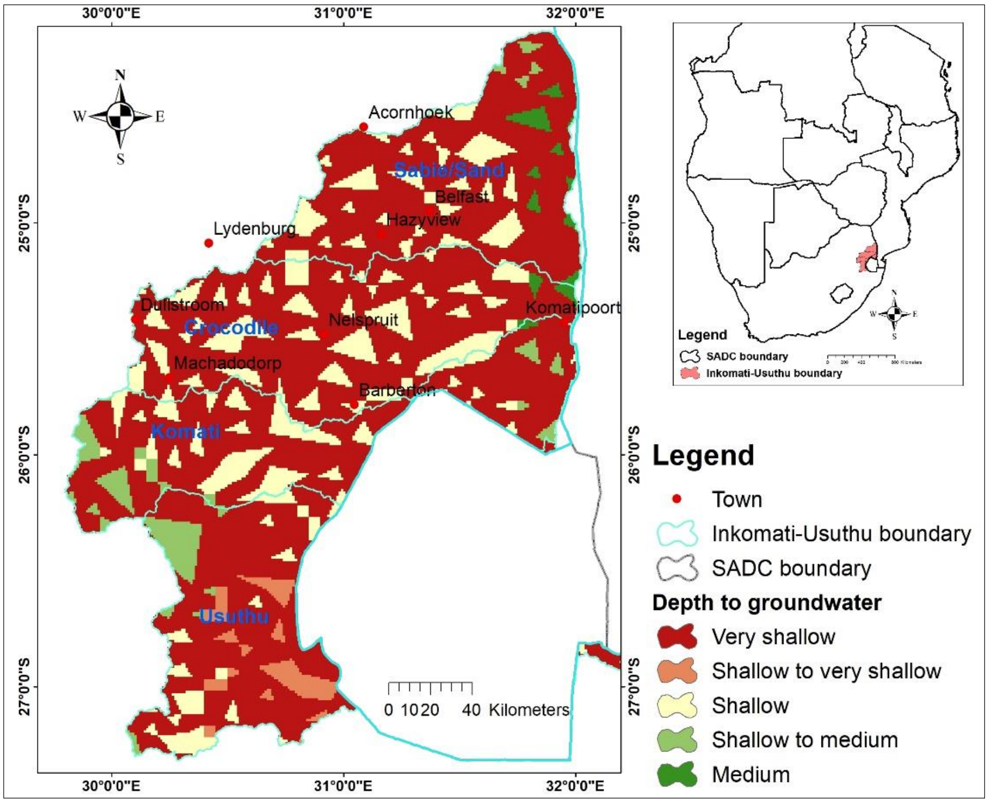


Figure 3.10. Reclassified surface criteria: Depth to groundwater in the Inkomati-Usuthu Catchment Management Agency

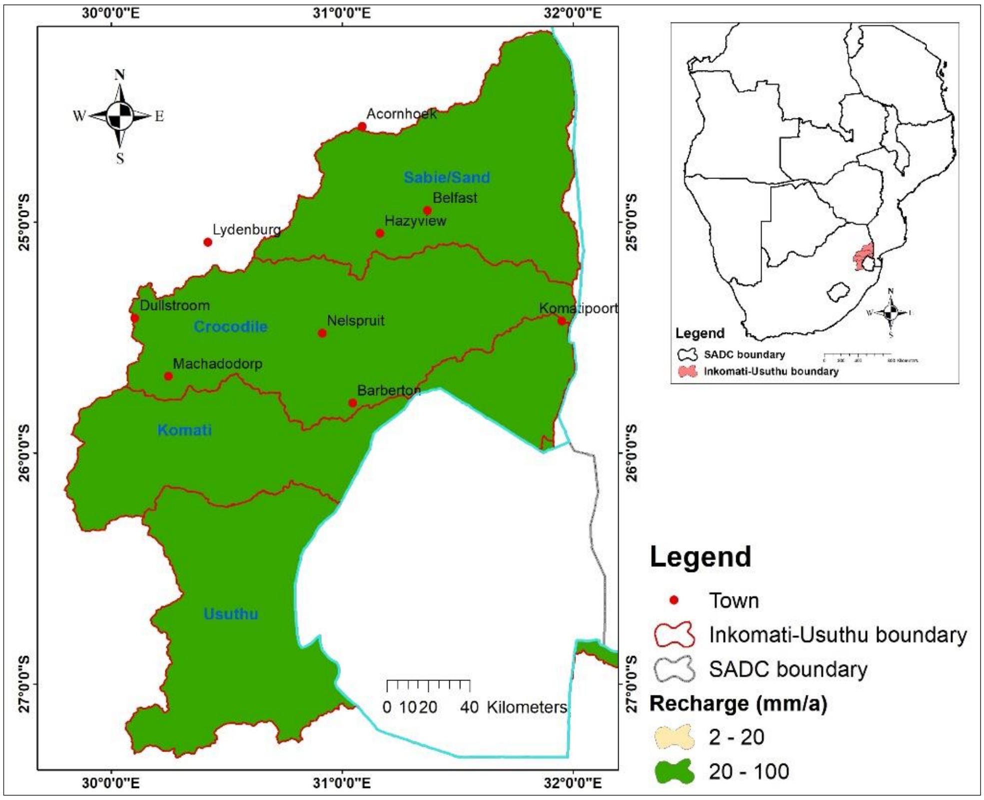


Figure 3.11. Groundwater recharge in the Inkomati-Usuthu Catchment Management Agency

3.3.1.3 Socio-economic criteria

To be profitable and generate benefits for farmers, the technology needs to be situated in close proximity to markets and must have public acceptance, especially in areas with low population density.

Proximity to major roads

Proximity to major roads was used as an indicator for access to market as reported in Owusu et al. (2017b). Road network data was obtained from SADA (2006) and reclassified following a buffer operation (Figure 3.12; Table 3.3). Range 0-100 m representing 1.8% of the total area was marked as unfavourable, while the remaining classes were apportioned ranks from “2” to “5”, with the farther distance (>3 000 m), requiring longer travel times being less favourable for the ASR technology, as shown in Table 3.3.

Population density

Population density was also used as criteria for site suitability, and the data with a resolution of 1 km was obtained from https://www.worldpop.org/geodata/listing?id=77. There were differences in the population densities in the study area. Former homelands and towns were crowded, while the other regions are less crowded. The population densities were reclassified into 5 classes, with areas of low population density being ranked high (5), as it is not preferred to install BIT in crowded areas. However, there should be good road network to access markets in high density areas. The reclassified and ranked data are shown in Figure 3.13 and Table 3.3.

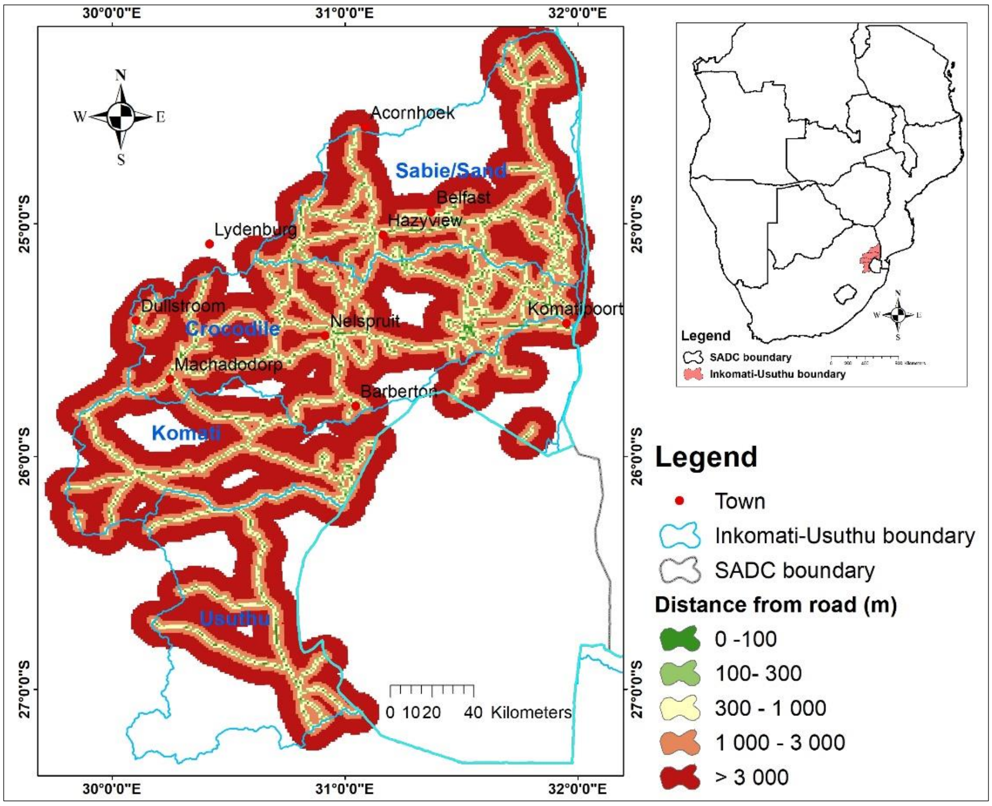


Figure 3.12. Reclassified socio-economic criteria: Distance from road in the Inkomati-Usuthu Catchment Management Agency

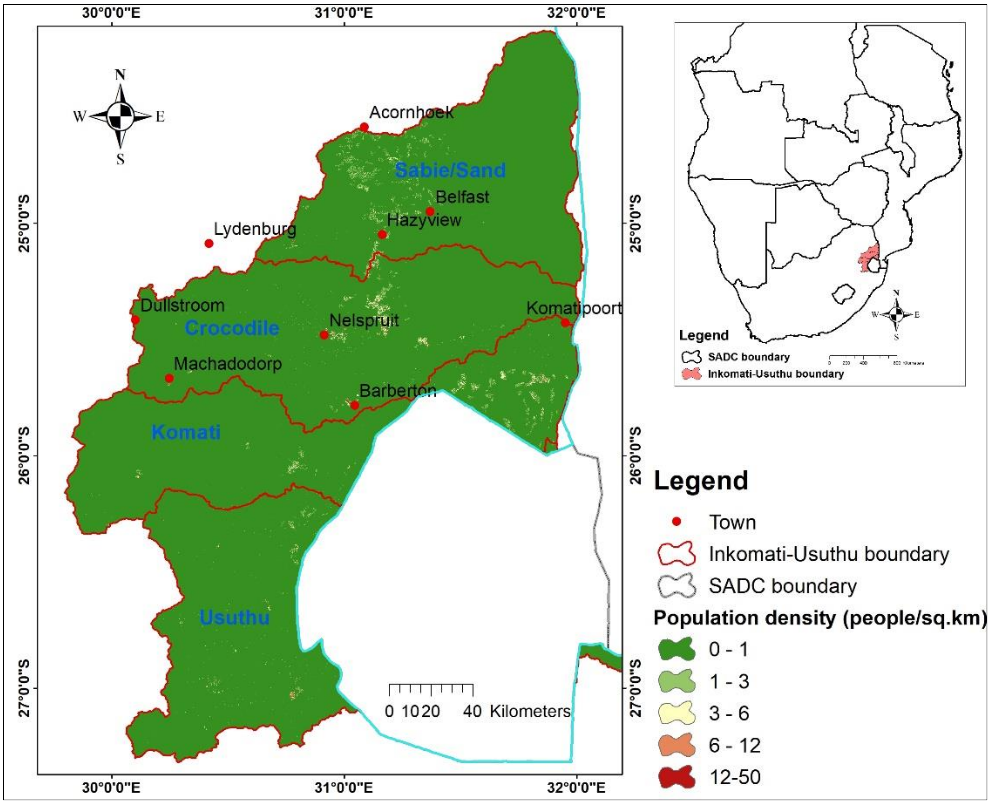


Figure 3.13. Reclassified socio-economic criteria: Population density in the Inkomati-Usuthu Catchment Management Agency

Table 3.1. Summary of reclassified surface and subsurface criteria in the Inkomati-Usuthu Catchment Management Agency

Suitability score	Landcover	Area (%)	Soil	Area (%)	Rainfall	Area (%)	Geology	Area (%)	Depth to groundwater	Area (%)
1	Bare ground and degraded	19.8	Sandy clay	20.1	400-650	22.9	Mafic and extrusives	46.8	Very shallow	76.3
2	Open bush	19.7	Sandy clay loam	1.5	650-800	28.2	Ultramafic intrusives	10.5	Shallow to very shallow	0.2
3	Cultivated	30.8	Loamy sand	13.3	800-1 000	27.5	Acid and intermediate lavas	5.9	Shallow	18.3
4	Thicket bush and woodlands	24.1	Sandy loam	62.5	1 000-1 200	18.5	Compact sedimentary	5.6	Shallow to medium	3.8
5	Grassland	5.6	Sandy	2.7	1 200-1 400	3.0	Unconsolidated sedimentary	31.3	Medium	1.3

Table 3.2. Soil texture classification and associated infiltration rates (Hillel, 1998)

Soil type	Steady infiltration rate (mm/hr)	Suitability score
Sands	> 20	5
Sand and silty	10-20	4
Loams	5-10	3
Clayey	1-5	2
Sodium clayey	< 1	1

Table 3.3. Summary of reclassified surface and socio-economic criteria in the Inkomati-Usuthu Catchment Management Agency

Suitability score	Drainage density	Area (%)	Slope (%)	Area (%)	Population density (people/km^2)	Area (%)	Road Proximity from road (m)	Area (%)
5	0-0.5	4.9	0-5	63.9	0-1	98.7	0-100	1.8
4	0.5-0.8	8.1	5-15	17.0	1-3	0.9	100-300	3.7
3	0.8-1.0	15.0	15-40	7.6	3-6	0.4	300-1 000	11.4
2	1.0-1.2	46.2	40-60	6.8	6-12	0.1	1 000-3 000	26.9
1	1.2-1.3	25.7	> 60	4.7	12-50	0.0	> 3 000	56.2

3.3.2 Analytic Hierarchical Process (AHP)

The AHP weighing approach within a GIS-based MCDA model developed by Saaty (1980) to analyse complex decisions by creating pairwise comparisons was used in this study. The AHP allows for relative measurement between elements. AHP is utilised within the spectrum of decision analysis and operational research, where decision analysis allows for individual choices among predefined alternatives to solve a complex set of systems (Brunelli, 2014). AHP provides a means of assigning weights to the different criteria and was applied to various land suitability assessments, from watershed planning to agricultural land use (Motuma et al. 2016; Yalew et al. 2016) and solar mapping (Schmitter et al. 2018). Weighting allows for a degree of preference to be made relative to the criterions. The AHP method is flexible to integrate both subjective and objective components of the decision process while limiting bias in the decision-making process by incorporating a 'consistency check' (Saaty, 1980). AHP was used in this study to calculate weights for the reclassified and standardised criteria, by first developing a pairwise comparison matrix based on Saaty (1980). Each criterion was assigned an appropriate weight, which reflected expert opinion and available literature. Each criterion is compared one by one to every other criterion in a pair-wise comparison matrix. A 1-9-point scale of importance was used, with 9 being the most important. Each score was then normalised and converted into relative weights. The weights computed using the AHP approach were comparative weights of individual criterion, based on their assigned ranks. The consistency ratio (*CR*) given in Equation 1 was used to identify and correct the logical inconsistency of the pairwise comparison matrix developed based on experience or expert judgement.

Each matrix is checked for consistency throughout the process by calculating the following *CR* from the consistency index (CI) and dividing it by the random index (*RI*) (Saaty, 1980):

The consistency index (*CI*) given in Equation 2 forms an input for determining the *CR*.

$$CR = \frac{CI}{RI} \quad [1]$$

where *CR* is the consistency ratio, *CI* is consistency index, *RI* is the random index.

$$CI = \frac{\lambda_{max} - n}{(n-1)} \quad [2]$$

where λ_{max} is maximum eigenvalue, *n* is the number of criteria or count.

The random index (*RI*) was presented in a table by the Oak Ridge National Laboratory for matrices with up to 15 rows (Saaty, 1980). In cases where the *CR* value is greater than 0.1, the assigned weight of the criterion from judgement is classified as inconsistent or unreliable due to its randomness and thus need modification, while values less than 0.1 are acceptable (Saaty, 1988; Yalew et al., 2016).
Once the assignment of weights is complete, quantification of criteria was conducted through pairwise comparison matrices within each hierarchal structure and then normalised.

3.3.3 Weighted overlay analysis

The final stage of the suitability analysis was the aggregation of the suitability factors to produce the final suitability map. Weighted overlay analysis was performed in ArcGIS considering the standardised criteria and their associated weights (Drobne and Lisec, 2009). The weighted overlay spatial analysis tool assessed the suitability index for a pixel by multiplying the suitability score and the weight – for the pixel. Summation of these results yielded a suitability map (S), based on Equation 3 (Pramanik, 2016; Yalew et al., 2016; Owusu et al., 2017b).

$$S=\sum W_i x_i \qquad [3]$$

where *S* is suitability, W_i is weight of factor *i,* x_i is criterion score of factor *i*.

3.3.4 Sensitivity Analysis

Many studies on MAR suitability perform an automated sensitivity analysis by changing inputs and observing the response of outputs. Sensitivity analysis accounts for data uncertainty and the subjectivity in decision-making. A sensitivity analysis was applied to estimate the robustness of the AHP weighting technique and to estimate the criteria or thematic factors that most affect its outcome (Babiker et al., 2005; Gibson and Campana, 2018). This was done by creating scenarios where one factor was reduced by 50% while the difference was evenly distributed among the other factors. Multiple simulations were conducted until all factors were reduced by 50%.

3.3.5 Bhungroo Irrigation technology and Solar irrigation pumping suitability mapping

The objective of this study was to identify the geo-spatial potential of solar-based PV pumping for irrigation taking into account not only solar radiation but also the availability of groundwater resources from Bhungroo Irrigation Technology (BIT) and linkage to markets.

Some studies (Schmitter et al., 2018; Nino et al., 2017) have assessed the suitability of specific areas for solar water pumping and smallholder irrigation from groundwater (Worqlul et al., 2017) using a Multi-Criteria Decision Analysis in Geographic Information System software programs (MCDA-GIS). In this process, a decision maker evaluates alternatives combining different decision criteria information to find the best solution to a specific problem. For this study, the interest is to guide decision-makers to determine the most suitable sites for the implementation of a successful solar water pumping with use of groundwater from the BIT technology.

Similar to the assessment of the requirements under BIT suitability, each mapping is made unique by the selection of criteria (nature and number), how they were translated into mapping, suitability and what weights are given to each of them. Based on experiences from India (Paul, 2013; Naireeta Services, 2015), Ethiopia (Schmitter et al., 2018) and Ghana (Owusu et al., 2017b), the essential requirements considered for mapping of BIT and solar water pumping included surface, subsurface and socio-economic conditions (Bunsen and Rathod, 2016). The surface requirement included biophysical features such as land-use/land cover type, soil type, rainfall, drainage density and slope of the terrain, and solar irradiation, while the subsurface requirements focused on storage capabilities of the aquifer and included depth to groundwater, and geology. The socio-economic conditions included population density and proximity to the roads for accessing the market.

3.3.5.1 Data sources

The land use data with a 20m resolution was obtained from South African Land cover (2018). The land cover influence surface runoff and gives information on the availability of land for implementation of BIT and solar water pumping. Waterbodies, wetlands, conservation and protected areas were ranked “0”, meaning they were excluded from the overall analysis. The geological indicators of lithology, were derived from geological maps developed by Council of Geoscience (2013). Maps containing data on the hydrogeology (depth to water table, recharge) were obtained from SADC-GMI (2018).

Solar irradiation data with a 250 m resolution was obtained from ESMAP (2020). The long-term energy availability of solar resource at any location is given by the global horizontal irradiation (GHI), which is the sum of direct and diffuse irradiation components received by a horizontal surface (ESMAP, 2020). GHI is measured in kilowatt hours per square metre (kWh/m^2). The GHI allows comparing the natural conditions for implementation of any PV technology without considering a particular technical design and mode of operation. However, GHI is modulated by local air temperature, wind and snow, atmospheric pollution, dust, and some other geographical factors at any particular site, hence it does not fully describe the actual potential for PV power production.

Slope is an important factor that controls runoff potential (Magesh et al., 2012). Flat slope is good for infiltration, while steep slope causes runoff. Slope was analysed using the 30m-resolution DEM from SRTM obtained from RCMRD (2020).

Soils with larger particle size will be the most suitable for surface infiltration as the infiltration rate increases with the particle size (Hillel, 1998). The soil data was obtained from ISRIC report on Soil and Terrain (SOTER) database at scale 1:1 million (Dijkshoorn et al., 2008). Soils with very fine texture were ranked unsuitable as they have low infiltration rates that discourage recharge for the BIT.

Drainage density reflected the slope and permeability of soils, with steep slopes and low permeability soils typically resulting in a high drainage density not favourable to infiltration but also increasing recharge for the BIT suitability as there is more surface water available for recharge. A flow accumulation network was developed from the 30m-resolution Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM), whereby the flow for each pixel was computed and the upstream accumulation was determined (Jenson and Domingue, 1988).

The depth to groundwater should provide enough space for the recharge water to occupy. The depth to groundwater should be provide enough space for the recharge water to occupy. Shallow groundwater level is less favourable than deep groundwater levels for BIT, but are suitable for solar water pumping, especially with small and more affordable pumps. Depth to the static water level is a controlling factor used to identify potential groundwater rise (Smith and Pollock, 2012). A range of 30-70 m depth of borehole is most suitable for the ASR technique in the form of BIT (UNFCCC, 2014).

Proximity to major roads and towns indicated access to markets as reported in Owusu et al. (2017b). Road network data was obtained from SADA (2006) and reclassified following a buffer operation. Distance from road of 0-100 m represented 1.8% of the total area was marked as most favourable site, while the farther distance (>3 000 m) was less favourable for the ASR technology and solar water pumping.

Population density data with a resolution of 1 000 m was obtained from https://www.worldpop.org/geodata/listing?id=77. There were differences in the population densities in the study area, with towns and former homelands being crowded, while the other regions are less crowded and more favourable for solar water pumping and BIT technology. The population densities were reclassified into 5 classes in the next section.

3.3.5.2 Reclassified criteria maps

Each criterion was reclassified into appropriate five classes in GIS environment mostly using Jenks Natural Breaks or natural groupings inherent in the data (Smith and Pollock, 2012). The classes were then standardised using a common scale of 1-5 (where 1 = very low suitability (maroon red colour), 2 = low suitability (light maroon red), 3 = medium suitability (yellow colour), 4 = high suitability (light green colour) and 5 = very high suitability (dark green colour)). Waterbodies, wetlands, conservation, protected areas, dams and areas with a solar irradiation lower than 1 300 kWh m^{-2} y^{-1} (Schmitter et al., 2018) were excluded from the final suitability map, and were assigned scale of zero. Standardization by reclassification helped to convert each criterion map to a uniform measurement scale for easy comparison and overlay analysis (Yalew et al., 2016).

The reclassified maps for land use /cover, solar, population density, geology-lithology, soil, annual rainfall, drainage density, depth to groundwater, slope, proximity to road and town (population density dependent, are shown in Figure 3.14-Figure 3.23.

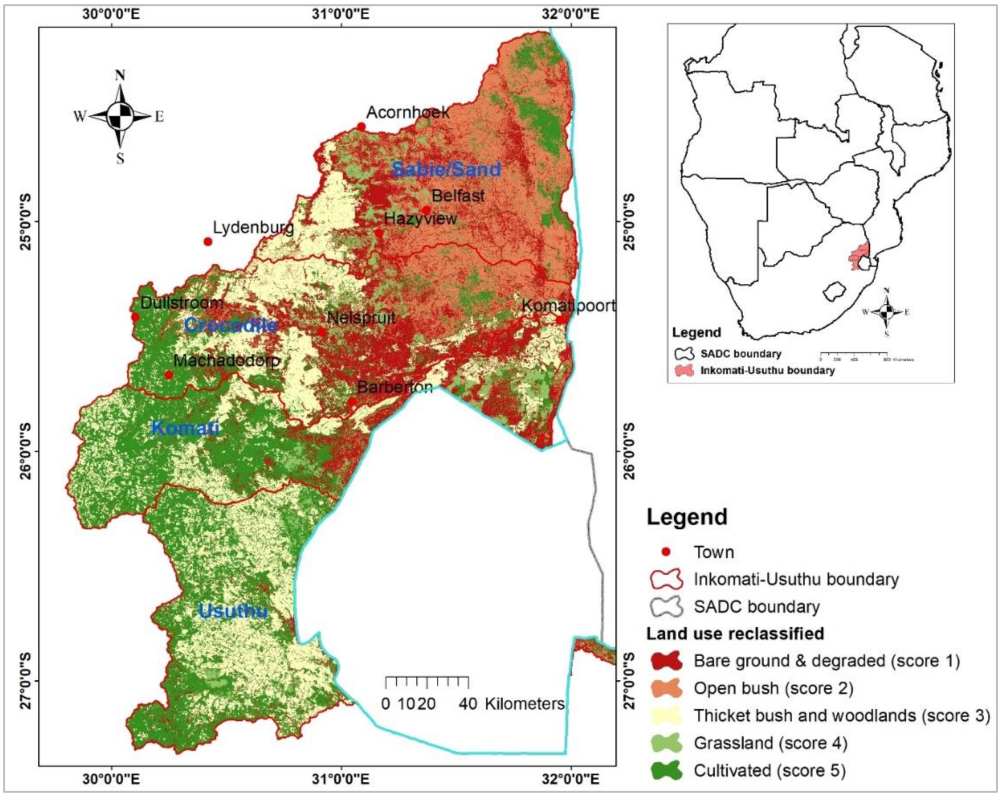


Figure 3.14. Reclassified land cover in the Inkomati-Usuthu Catchment Management Agency

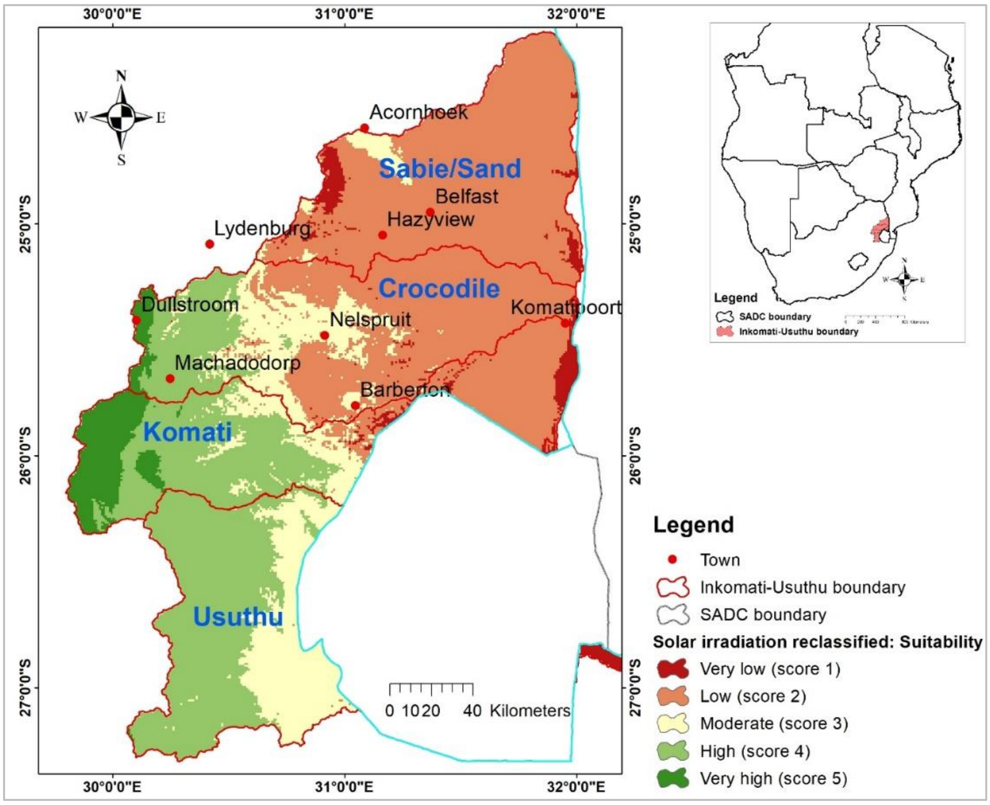


Figure 3.15. Reclassified solar irradiation in the Inkomati-Usuthu Catchment Management Agency

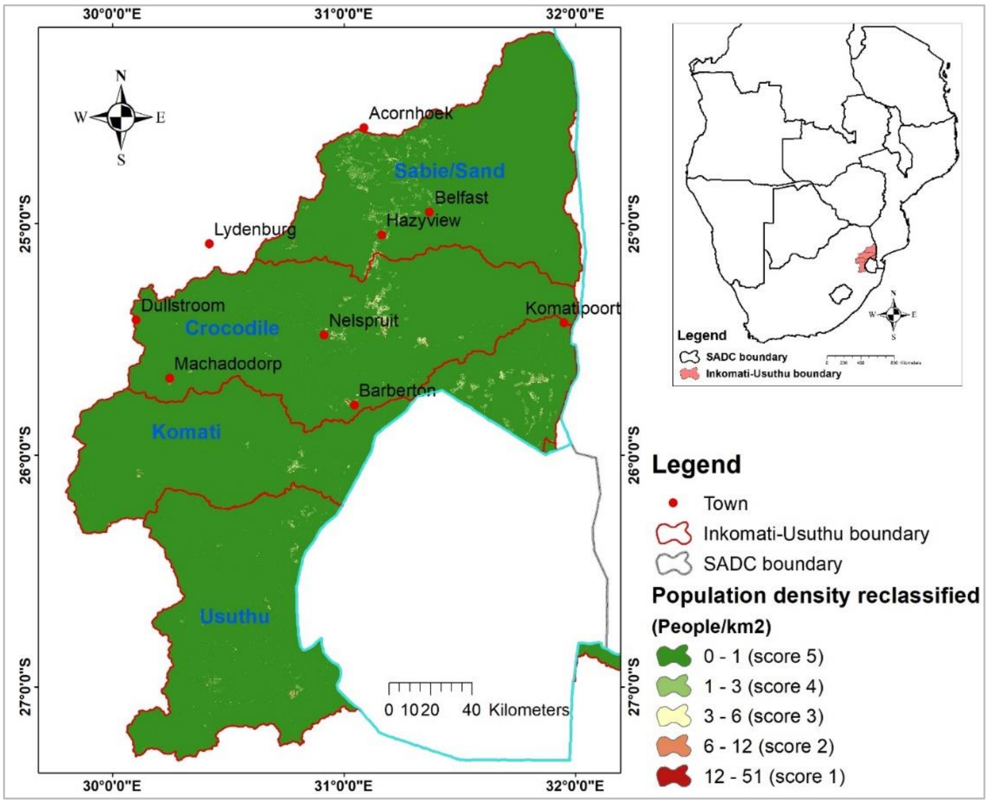


Figure 3.16. Reclassified population density in the Inkomati-Usuthu Catchment Management Agency

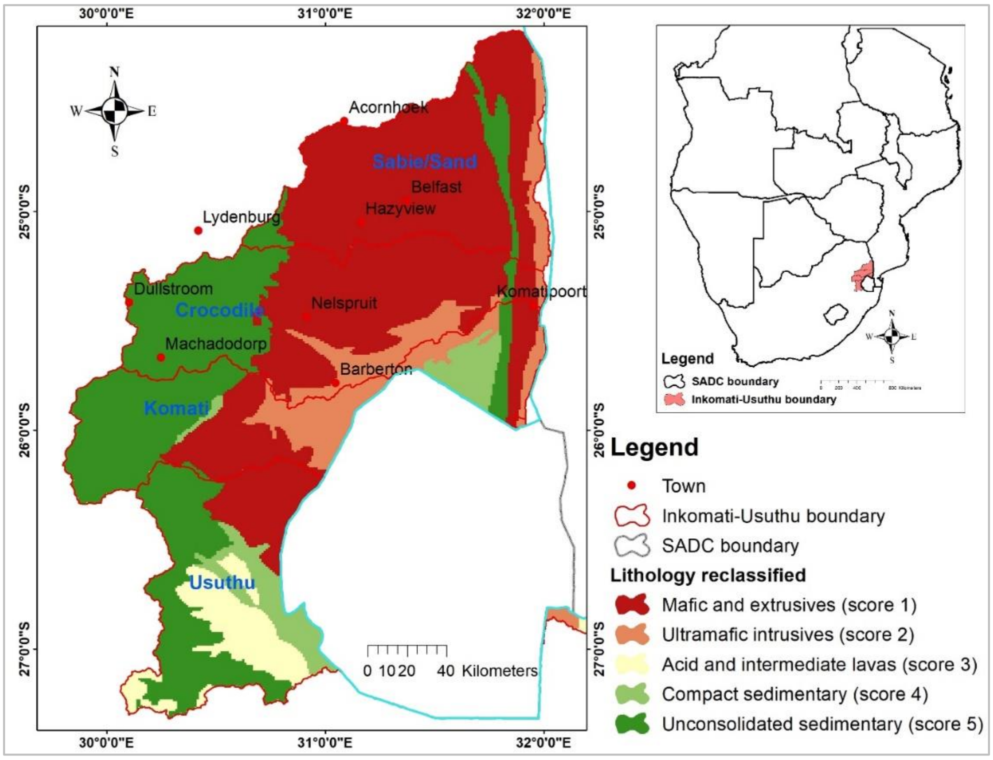


Figure 3.17. Reclassified geology /lithology in the Inkomati-Usuthu Catchment Management Agency

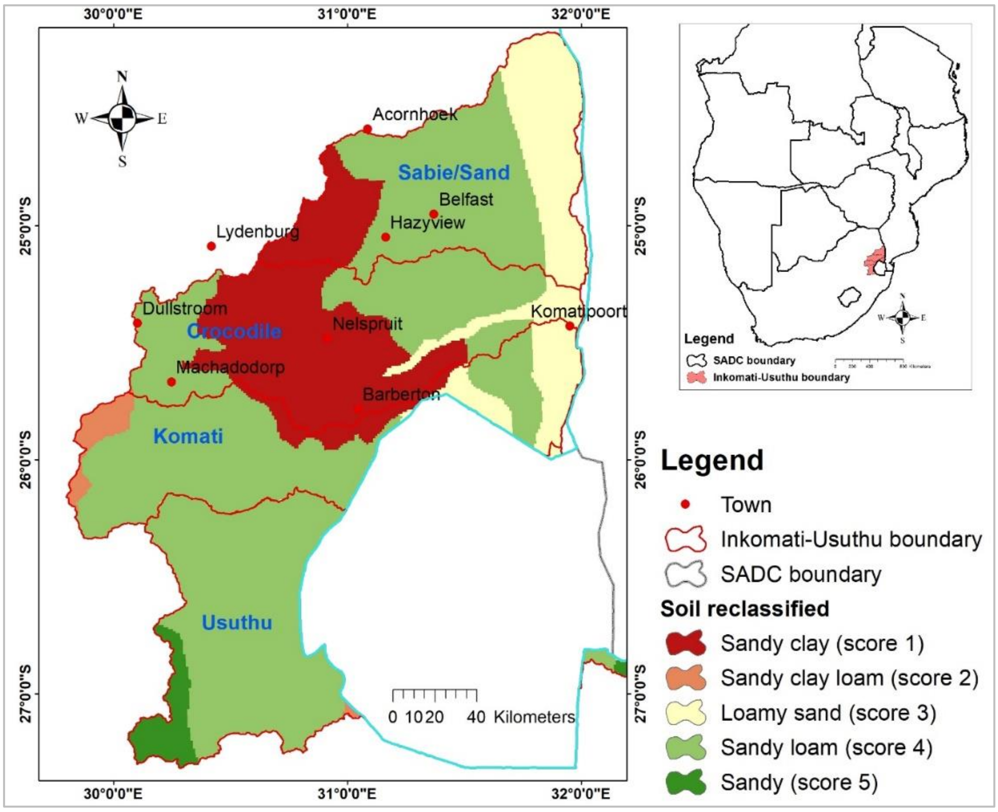


Figure 3.18. Reclassified soil in the Inkomati-Usuthu Catchment Management Agency

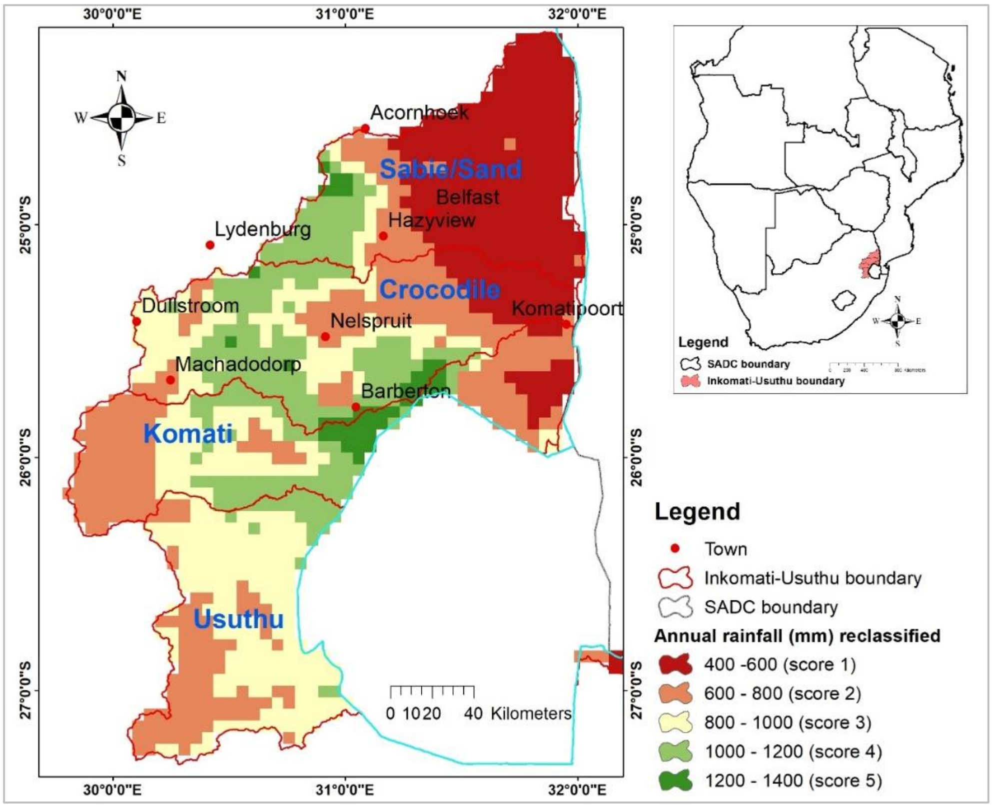


Figure 3.19. Reclassified annual rainfall in the Inkomati-Usuthu Catchment Management Agency

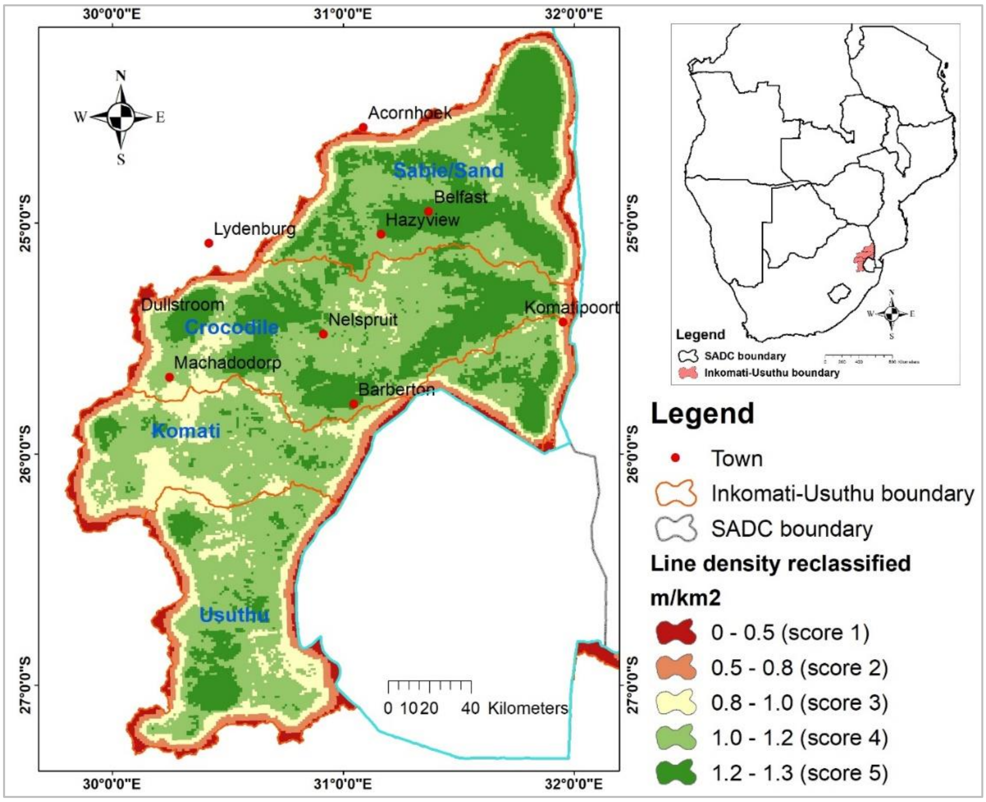


Figure 3.20. Reclassified drainage density in the Inkomati-Usuthu Catchment Management Agency

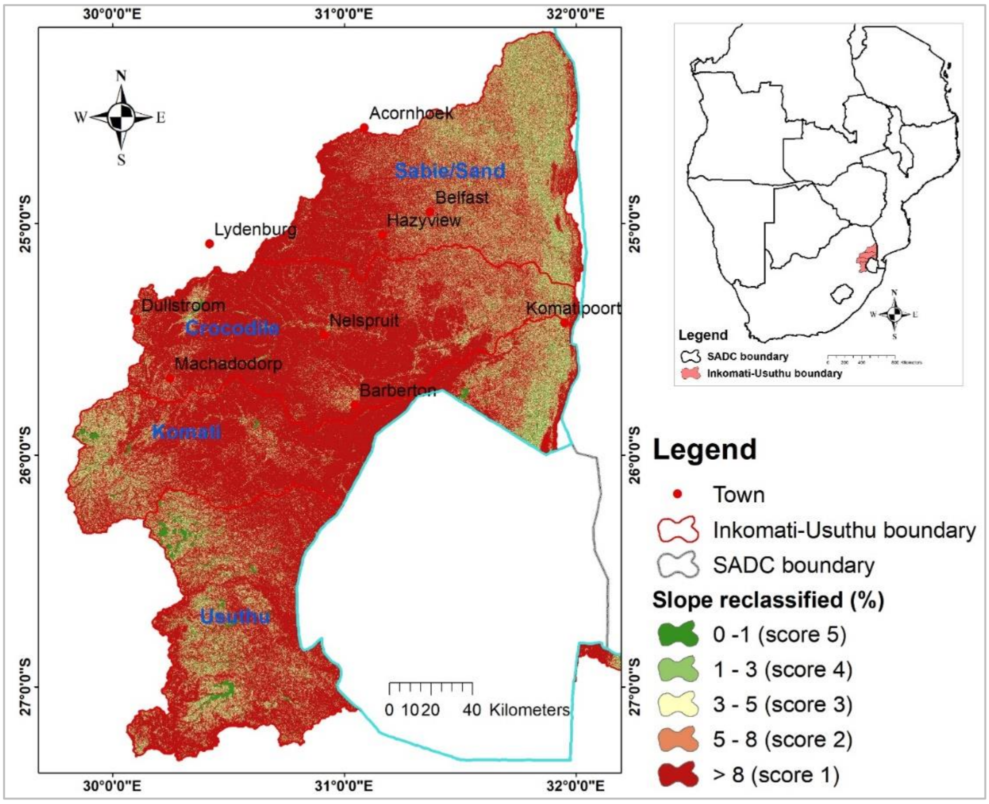


Figure 3.21. Reclassified slope to groundwater in the Inkomati-Usuthu Catchment Management Agency

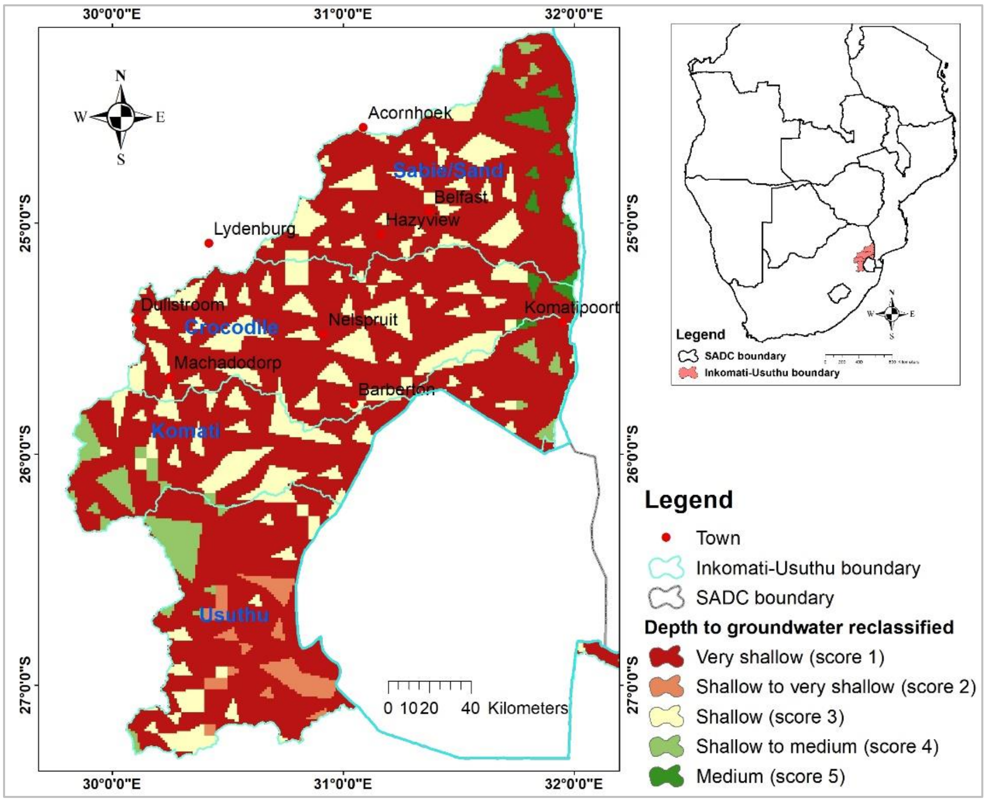


Figure 3.22. Reclassified depth to groundwater in the Inkomati-Usuthu Catchment Management Agency

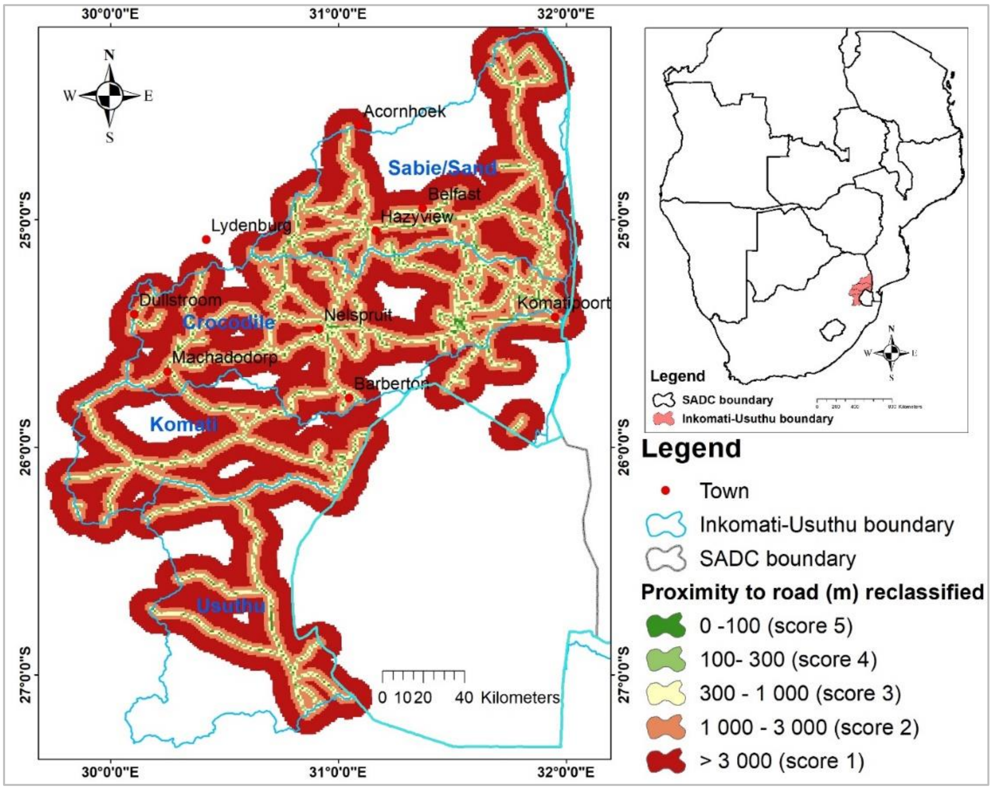


Figure 3.23. Reclassified proximity to road in the Inkomati-Usuthu Catchment Management Agency

3.3.5.3 Technical specifications of solar PV pump

The lifting capacity of the pump and related solar energy requirement is an important input in assessing feasibility, as this also determines which water resources and geographical areas are suitable. This study focused on smallholder solar water pumping options, as solar pumps that extract water from deep boreholes involve large capital investments generally beyond the reach of smallholder farmers and are not always readily available. Therefore, for this study, smallholder farms of 1 ha, requiring maximum requirement for solar power of 1 kW was considered (López-Luque et al., 2015). Hence, a solar pump requiring a minimum irradiation of 1 kWh m^{-2} with a suction head limitation of 30 m was selected (Schmitter et al., 2018). A pairwise comparison matrix was applied to the reclassified maps based on method by Saaty (1977). The weighting factors were initially determined based on expert knowledge and then fine-tuned through literature.

3.3.6 Performance evaluation of BIT for conjunctive groundwater and surface water use, coupled with solar irrigation pumping

The objective of this section is to assess suitable areas for evaluate the performance of BIT and solar irrigation pumping in the Inkomati-Usuthu Catchment Management Area in Mpumalanga Province, South Africa, using weighted multi-criteria decision analysis (MCDA) in ArcGIS environment. The questions addressed in this study are: (1) How can surface, subsurface and socio-economic datasets be combined to assess spatial BIT suitability, and (2) How does BIT suitability vary within a catchment? The creation of MAR suitability maps promotes the successful application of MAR and are increasingly used in sustainable groundwater management plans. This section are: (1) Is the water quality suitable for irrigation? (2) How much water is recharged, and recovered for irrigation, (3) How much energy is used and saved, and (4) How much income is realized from the crop production. This evaluation adds to the work reported by Pavelic et al. (2019) in Vietnam.

3.3.6.1 Data collection

Water quality sampling and analyses
The main purpose of the water quality sampling is to establish the baseline data of the water quality in the study areas and to determine if the Bhungroo technology impacted the water quality. In addition, water quality is used as a tracer to track the source of the water. Therefore, additional isotopic analyses were done on the samples to determine the ratio of artificial recharge to existing groundwater in the aquifer.

Groundwater samples were collected from the Bhungroo borehole (White River BH1), as well as from at least two other boreholes (White River BH2 and White River BH3) other boreholes at White River site, while for Schoemansdal site, samples were only collected from the Bhungroo site (Schoemansdal BH). Samples were collected once before installation of the Bhungroos to provide baseline quality and four times after installation to monitor any water quality changes (Table 3.4). In addition to the groundwater quality monitoring, rainfall was sampled during the wet season at Schoemansdal site.

Table 3.4. Dates for water quality sampling for chemical and isotope analyses

Data	Groundwater sampling	Rainwater sampling
13/05/2021	X	
14/12/2022	X	
04/03/2022	X	X
29/06/2022	X	
18/08/2022	X	

Water quality samples from boreholes were obtained by purging for about 5 minutes before samples were collected into 500 mℓ high density polyethylene bottles in duplicate. In-situ parameters such as pH, conductivity and total dissolved solids (TDS) were measured using ExStik EC500 pH/Conductivity/Total dissolved solids/Salinity meter. Samples are collected, cooled below 4°C in a cooler box with ice cubes and transported to the University of North West Laboratory in Potchefstroom.

For isotopic water sampling, borehole or Bhungroo water was collected into a 500 mℓ plastic container after purging for about 5 minutes. The plastic bottles were completely filled, making sure the sampling container has no bubbles and is air tight. Samples were labelled, covered with black plastic to avoid exposure to sunlight, stored in cooler box and transported to iThemba Labs in Johannesburg for isotope analysis.

The water quality results were compared with the standard for irrigation water use target range values. Target range values, as a matter of policy are values the DWAF (1996) strives to maintain for the quality of South Africa' s water resources such that they remain within the no effect range, to prevent negative impacts on crop production and environment.

3.3.6.2 Stable Isotope Analysis

Water deuterium (D)/hydrogen (H) ($^2H/^1H$) and oxygen $^{18}O/^{16}O$ ratios (Equation 1) were analysed in the laboratory of the Environmental Isotope Laboratory (EIL) of iThemba Labs, Johannesburg. The equipment used for stable isotope analysis consists of a Los Gatos Research (LGR) Liquid Water Isotope Analyser. Laboratory standards, calibrated against international reference materials, are analysed with each batch of samples. The analytical precision is estimated at 0.5‰ for O and 1.5‰ for H. Similarly, Equation 4, applies to D/H ($^2H/^1H$).

$$\delta^{18}O(\text{‰}) = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000 \qquad [4]$$

Where delta values are expressed as per mil deviation relative to a known standard, in this case standard mean ocean water (SMOW) for $\delta^{18}O$ and δD.

Standard procedures were followed for data collection and laboratory analyses (Dugan et al., 1985). The isotopic compositions of water were reported as the deviation of Deuterium ($^2H/^1H$) or oxygen-18 ($^{18}O/^{16}O$) ratio from that of Vienna Standard Mean Ocean Water (VSMOW) in parts per thousand ‰. Local Meteoric Water Line (LMWL) was plotted from precipitation data on ^{18}O and ^2H results. This LMWL was compared to Global Meteoric Water line (GMWL) and similar studies on isotopes conducted across South Africa to understand conditions under which recharge occurred in groundwater and in the Bhungroo borehole.

3.3.6.3 Sodium hazard (Sodium Adsorption Ratio)

The suitability of irrigation water is determined not only by the total amount of salt present but also by the kind of salt. Soil and crop production problems develop as the total salt content increases, and special management practices may be required to maintain acceptable crop yields. The concentration and composition of soluble salts in water determines its quality for irrigation. Two criteria used for evaluating water quality for irrigation purposes used were water salinity (EC) and sodium hazard (sodium adsorption ratio -SAR) (Magdoff and van Es, 2021).

3.3.6.4 Groundwater recharge estimation

Recharge can be defined as "the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone" (Freeze and Cherry, 1979). Recharge remains an elusive process to quantify. This is especially so because it depends not only on precipitation amount and intensity but also on soil type, geology, soil-moisture status, vegetation cover and condition, slope, cultivation practices, and most of all, on evapotranspiration. In this study, the recharge process assumed steady-state conditions from rainfall with no contribution from deep-seated formations. Change in land use and consequently recharge rate can drastically affect the assumptions about hydrologic steady state (Sharma, 1986), but were not taken into consideration for this study.

There are several different approaches that can be implemented to estimate groundwater recharge and use of more than one method is recommended because of the difficulty in assessing the accuracy of recharge estimates (Sharma, 1986). Hence, we applied two environmental tracer methods, the Chloride Mass Balance (CMB), and isotope methods, which assume the steady-state conditions (Naranjo, 2015).

The annual replenishable groundwater recharge from the Bhungroo sites includes the following components: 1) natural recharge from harvested rainfall runoff; 2) recharge through the filtration bed and borehole into the aquifer and 3) deep percolation from irrigation. As limited irrigation is practiced and high temperatures experienced in the study sites, we focused on the first two components of the groundwater recharge.

3.3.6.5 Chloride Mass Balance (CMB)

An environmental tracer suitable for determining the movement of water must be highly soluble in water, conservative and not substantially taken up by vegetation. The chloride ion satisfies most of these criteria and was therefore considered a suitable tracer in this study to apply the conservation of mass for the tracer. Traces of chloride in saturated zone, taken at different points give long-term averages (> year) and an average value in space and time, which is difficult to obtain using physical methods. This method is convenient, fast and cheap, while the main disadvantage of the CMB is the uncertainty in the determination of the wet and dry chloride deposition and the assumption that no chloride is derived from weathering within the catchment. The CMB has been successfully used to estimate the recharge for different catchments in arid and semi-arid regions (Izbicki et al., 2002).

CMB is based on the assumptions that there is no storage of chloride in the unsaturated zone, and therefore precipitation and dry atmospheric deposition are the only sources of deposition in groundwater and in surface runoff. Measured chloride concentrations are at depth high enough that seasonal variations in concentrations are small, the concentrations in surface runoff are the same as that in precipitation (McNamara, 2005). Long-term records of CMB variables are rare, hence this study estimated both natural and artificial recharge from available 2 years of data.

The CMB method requires the amount of precipitation, the concentration of chloride dissolved in rainfall, and the concentration of chloride dissolved in groundwater as inputs (Obuobie et al., 2010). Therefore, CMB was used to estimate natural and artificial groundwater recharge using Equation 5.

$$R = \frac{Cl_P}{Cl_{gw}} * P \quad [5]$$

Where *R* (mm/yr) is recharge flux, *P* is average annual precipitation (mm/yr), Cl_P (mg/ℓ) the weighted-average chloride concentration in precipitation, Cl_{gw} (mg/ℓ) is the average chloride concentration in groundwater. Field data collected from groundwater from May 2021 to August 2022 served as inputs to recharge determination. A total of 5 samples were collected from White River and Schoemansdal sites. Due to challenges with the rain gauges installed at two sites, an average of 6 months chloride rainfall data of 2 mg/ℓ (Magombeyi et al., 2019) from a catchment near the study sites was used as an estimate of yearly mean chloride concentrations in rainfall for White River and Schoemansdal (Nkomazi) sites. This rainfall chloride estimate used was justified because the stable isotope contents appear fairly constant in time and they fingerprint the existence of different recharge episodes, if controlling factors such as temperature, humidity remain fairly stable (Pelig-ba, 2009).

3.3.6.6 Isotope method

Isotopes of ^{2}H and ^{18}O are commonly used in recharge studies to simulate the movement of water, because they form a part of the water molecule and act as ideal conservative tracers. The isotopic composition of water changes in response to evaporation of the water and precipitation, as well as climatic differences. This change in the isotopic ratios can be used as a tool for characterizing the path water has taken through the hydrologic cycle (Clark and Fritz, 1997). The Global Meteoric Water Line (GMWL) is a global precipitation average of the isotopic relation between $\delta^{18}O$ and $\delta^{2}H$. Because of the changes that occur in the hydrologic cycle, a Local Meteoric Water Line (LMWL) is helpful for determining sources of groundwater recharge and for evaluating surface water and groundwater interaction (Eddy-Miller and Wheeler, 2010). The groundwater isotopic composition is an integrator of all recharge events as it reflects the mixed isotopic signature roughly in proportion to the amount of harvested runoff and ‘normal’ recharge (Coplen et al., 2000). The fraction of new water is assumed to be the recharge to groundwater.

3.3.6.7 Estimation of groundwater age

Groundwater age may be used to estimate recharge rates and to infer susceptibility of groundwater to anthropogenic activities at the land surface (McMahon, 2012; Clark and Fritz, 1997). In groundwater quality studies, recently recharged groundwater is commonly considered to be susceptible to contamination by persistent, soluble anthropogenic contaminants introduced at the land surface, while concentrations of naturally occurring contaminants related to geology can be elevated in premodern (pre-1950s) groundwater because they dissolve from geological materials of aquifer over long time periods (Lindsey et al., 2019).

The simplest groundwater age dating methods use binary bins of modern (post-1950s) and premodern (pre-1950s) by comparing the concentration of an atmospheric tracer like tritium (^3H) to a selected threshold. Tritium is a radioactive isotope of hydrogen (half-life 12.32 years) (Lucas and Unterweger, 2000). Because of the rapid increase and decrease of ^3H in precipitation during and after the period of atmospheric nuclear-weapons testing, it is often used to differentiate groundwater recharged before and after the early 1950s (McMahon, 2012). McMahon (2012) used a concentration threshold of ^3H greater than or less than 0.5 tritium unit (TU) and Thomas (2007) used 1 TU to differentiate modern from premodern water.

The tritium-based age classification system was used in this study as it is cheap and informative as a screening tool prior to selecting more expensive and complex age-dating tracers and methods (Lindsey et al., 2019). The disadvantages of using tritium include a low half-life and the decrease in tritium levels in the atmosphere since the bomb test stopped in 1960s. Therefore, appropriate measures at which the tritium dating technique is relevant is only about 4 to 5 half-lives, thereby limiting the applicability of the technique to only recently recharged waters (Abiye, 2013). Kazemi et al. (2006) reported that the tritium method is applicable for groundwater ages ranging from several months to about 30 years, and no further than about 50 years. The tritium results have implications for the susceptibility of groundwater to surface contaminants from runoff or to natural contaminants.

Groundwater age was estimated using Equation 6 (Kazemi et al., 2006; Lucas and Unterweger, 2000):

$$\text{Groundwater Age, } \tau \text{ (in years)} = -17.8 * \ln \left({}^3H_t / {}^3H_0\right) \qquad [6]$$

Where ^3H_t is measured tritium concentration in sample after some time, t; $^3H_0$ is tritium concentration in TU from precipitation. In most aquifers, geogenic tritium is insignificant (Boulton et al., 1993).

3.3.6.8 Quantification of the water recovery efficiency from the Bhungroo borehole

To understand how much of the infiltrated water is recovered for irrigation, an isotope tracer study was conducted. Based on the different signatures of the groundwater, surface runoff water and pumped irrigation water, we estimated the proportion of the different water sources from the abstracted irrigation

water (mixture of recently recharged and ambient groundwater) from Bhungroo borehole during the season was estimated from a simple mass balance (recovery efficiency). The stable isotopes of deuterium and oxygen-18 were used.
A two-component mixing equation (Katz et al., 1998) was used to estimate the relative amount of runoff water in the Bhungroo. Hence, the fraction of runoff (surface) water (F_{SW}) in the Bhungroo is defined by Equation 7:

$$F_{SW} = \frac{C_{BHGwell} - C_{gw}}{C_{sw} - C_{gw}} \quad [7]$$

Where, $C_{BHGwell}$ is the concentration of the tracers in the Bhungroo borehole, C_{gw} is the concentration of the tracers in groundwater and C_{sw} is the concentration of the tracers in surface water recharging the Bhungroo borehole.

For example, using stable isotope values of injection water and groundwater from Bhungroo borehole, the percent of injection water can be estimated using Equation 8 represented as follows:

$$F_{SW} = \frac{\delta_{BHGwell} - \delta_{gw}}{\delta_{sw} - \delta_{gw}} \quad [8]$$

Where, F_{SW} is as defined above, $\delta_{BHGWell}$ is the δ value of the Bhungroo borehole water (mixed); δ_{SW} is the δ value of the source water; and δ_{gw} is the δ value of native or ambient groundwater.

High differences in concentrations of the constituents in surface water, Bhungroo and groundwater result in relatively high precision for detecting the mixing proportions of surface water in groundwater.

3.3.6.9 Quantification of the irrigation water use and energy use

Estimation of irrigation water use
Water use was estimated by collecting data on the pump discharge per hour, number of irrigation events per week, duration of irrigation event, number of weeks per season, and the size of the field. The water use was calculated by multiplying pump discharge by duration of irrigation by number of irrigation events per season, then divided by field size. The water use was expressed in m^3/ha.season and m^3/ha.yr, assuming there are 3 growing periods in a year for vegetables.

Estimation of energy use for pumping irrigation water
The pump discharge was estimated on-site by timing the duration required to fill a 20-litre container, with an average of 6 readings used. Energy consumed by an electric pump (2.2 kW submersible pump) is given by energy use per irrigation event (8.8 kWh) multiplied by number of irrigation events per season. The yearly values are calculated by multiplying seasonal values by 3, based on the three-growing periods per year assumed. The carbon-dioxide emitted from a grid-connected electric pump was estimated, considering that every kilowatt-hour (kWh) produced, 1 kg of carbon dioxide (CO_2) is emitted, and 1.4 litres of water are used, and 0.37 g of particulate emissions are released in the atmosphere (de la Rue du Can et al., 2019; Eskom, 2015).

3.3.7 Interviews with solar stakeholders: Barriers and opportunities for solar irrigation pumping

Interviews and physical evaluations on technical, biophysical, financial, social, and environmental factors were carried out with different stakeholders to identify barriers and opportunities for solar irrigation adoption in South Africa. Contacts for stakeholders were obtained through web search and referrals. The stakeholders interviewed included solar pump companies (suppliers and or installers of solar irrigation systems), policy makers (government ministries and departments), international development agencies (e.g. funders, Non-governmental organizations), academic and research organizations (e.g. universities, and research in organizations), and solar powered irrigation users and user groups (individual, cooperative and group farmers). The questions in the questionnaire were tailor-made to each of the different stakeholders. These included how many solar powered irrigation installations are in their community; what business models are being applied or considered in overcoming financial barriers/risks to smallholder farmers; what incentives are available to encourage solar adoption and how sustainable and inclusive are they; what are the major barriers (technical, financial, institutional, policy, and social/cultural/gender) experienced in rolling out solar powered irrigation technologies; and what innovations are being implemented to improve the solar powered irrigation sector? Questions to academic institutions included presence or absence of any solar powered irrigation related content in the academic curriculum. Questions to farmers included how did they become aware of solar powered irrigation; what motivated the farmers to start using it; how was the solar powered irrigation system funded; to what extent does the system satisfy the crop water requirements at the farm; do they have sufficient knowledge to operate and maintain the system effectively; what are security risks to the solar powered irrigation system, and how much income is realized from the solar powered irrigation?

3.3.8 Guidelines for the installation and operation of the Bhungroo Irrigation Technology (BIT) and solar irrigation pumping bundle

To increase irrigation water availability and access at low energy costs during the dry season or periods, artificial aquifer recharge through Bhungroo Irrigation Technology (BIT) and solar irrigation pumping has been successfully implemented at the two sites in the Inkomati-Usuthu Catchment Agency, in White River and Schoemansdal in Mpumalanga Province in South Africa. Following this success, general guidelines were developed to ensure appropriate implementation of this bundled technology (artificial recharge and solar water pumping) to other dry areas and regions, in such a way as to cause no-harm to both humans and the environment. The BIT involves constructing a large underground filter box around a borehole to increase recharge and removing unwanted constituents or dirty from rainfall or rainwater harvested in to the borehole, and the pumping of irrigation water from the same borehole when needed using solar powered pump.

The guidelines included the site suitability assessment, location of services near the excavation site, excavation of the filter box, construction of bottom concrete slab, construction of filter box masonry walls, perforation of the borehole casing, laying of filter material in the filter box, water supply to recharge the aquifer through the filter box, operation and maintenance, monitoring the water levels and water quality in the Bhungroo borehole, water quality analysis before artificial recharge of the aquifer, water quality analysis after artificial recharge of the aquifer, evaluation of recharged water quality, assessment of water type from a piper diagram, recharge estimation into the Bhungroo borehole or aquifer, and assessment of the benefits of crop yield and income of artificial recharge pumped by solar pump from Bhungroo technology.

The installation of solar pump to pump water from the Bhungroo borehole includes, type of water pump, installation of the solar water pumping system, installation of an array frame structure, maintenance of solar modules/panels and pump, quantification of groundwater use from BIT, and quantification of energy and carbon dioxide emitted from pumping irrigation water from the Bhungroo.

CHAPTER 4: RESULTS & DISCUSSION

4.1 SUITABILITY MAPPING FOR MAR INJECTION METHOD IN THE FORM OF BHUNGROO IRRIGATION TECHNOLOGY

4.1.1 Analytic Hierarchy Process and Weighted overlay analysis of Bhungroo Irrigation Technology suitability mapping

An Analytic Hierarchy Process (AHP) was developed within a Multi-Criteria Decision Analysis to spatially delineate locations most suitable for BIT in the IUCMA. Results from the AHP weighted overlay method were expressed on a scale from 1 to 5, with 5 being very high suitability and 1 very low suitability for BIT. For this study, high BIT suitability indicates that, if a water supply of sufficient quantity and quality were available, surface, subsurface and socio-economic conditions are likely to be favourable for developing a BIT project. The criteria in order of importance based on weights included land use /cover, rainfall, population density, geology, soil, drainage density, proximity to road, depth to groundwater and slope (Table 4.1). These weights were derived from the AHP matrix presented in Table 4.1.

The nine spatial datasets were combined to generate a distribution of ASR in the form of BIT suitability across the IUCMA (Figure 4.1). The suitability shows constrained layers of wetlands, conservation and protected areas removed and are shown in white in the map (Figure 4.1). Land areas with very high suitability for BIT, accounts for 1% of the analysed land area in the IUCMA (184 km^2). These areas are located to the south of Barberton town (Figure 4.1). The result showed that around 92% (26 325 km^2) of the area was available for the technology with moderate to very high BIT suitable sites, and 8% (2 210 km^2) within very low and low class (Figure 4.2). The restricted areas of wetlands, conservation and protected areas accounted for about 23% (8 654 km^2) of the entire study area, which was approximately 37 200 km^2 (Figure 4.3).

Table 4.1. Pairwise comparison matrix for Multi-Criteria Decision Analysis. Depth to GW is depth of groundwater.

Matrix		Landuse/ cover	Soil	Geology	Slope	Rainfall	Drainage density	Road proximity	Population density	Depth to GW	Normalised principal Eigenvector (Weight)
		1	2	3	4	5	6	7	8	9	
Landuse/ cover	1	1	5	5	7	5	3	3	1	7	31.42%
Soil	2	1/5	1	1	5	1/5	1	1	1	3	9.23%
Geology	3	1/5	1	1	3	1	3	1	1	1	9.85%
Slope	4	1/7	1/5	1/3	1	1/3	1/3	1	1/3	1	3.79%
Rainfall	5	1/5	5	1	3	1	1	1	1	1	11.94%
Drainage density	6	1/3	1	1/3	3	1	1	1	1	1	8.01%
Road proximity	7	1/3	1	1	1	1	1	1	1	1	7.91%

Matrix		Landuse/ cover	Soil	Geology	Slope	Rainfall	Drainage density	Road proximity	Population density	Depth to GW	**Normalised principal Eigenvector (Weight)**
Population density	8	1	1	1	3	1	1	1	1	3	11.94%
Depth to GW	9	1/7	1/3	1	1	1	1	1	1/3	1	5.90%

Note: Consistency ratio (CR) was 8.6% < 10% for matrix larger than 4 by 4, hence the assigned weights and pairwise comparison matrix were consistent and acceptable (Saaty, 1980).

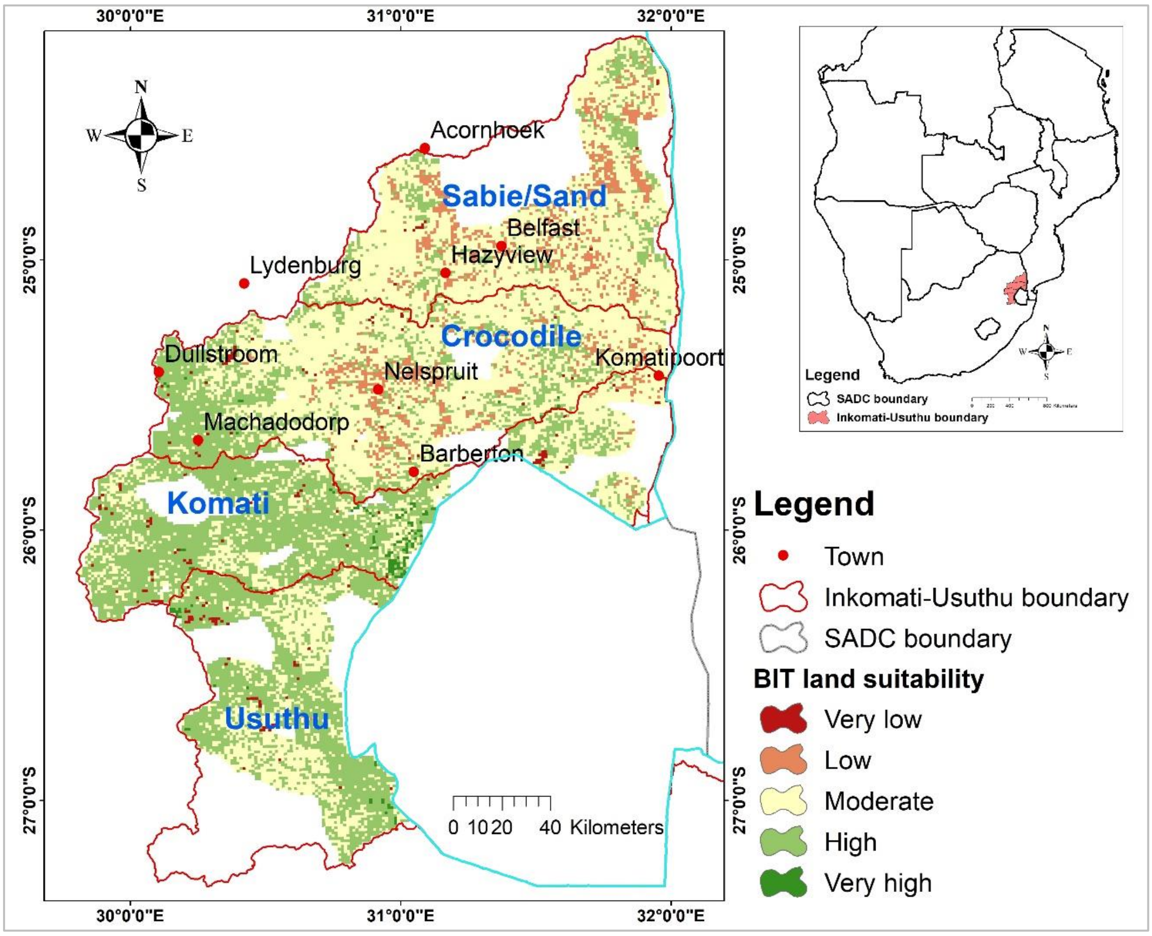


Figure 4.1. Bhungroo Irrigation Technology suitability map for Inkomati-Usuthu Catchment Management Agency

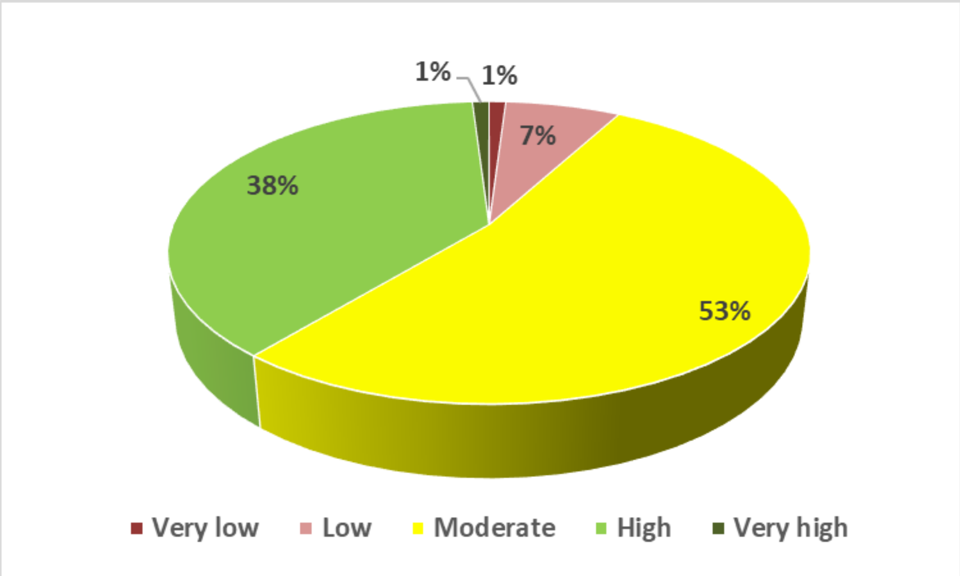


Figure 4.2. Weighted overlay results by percent of catchment area.

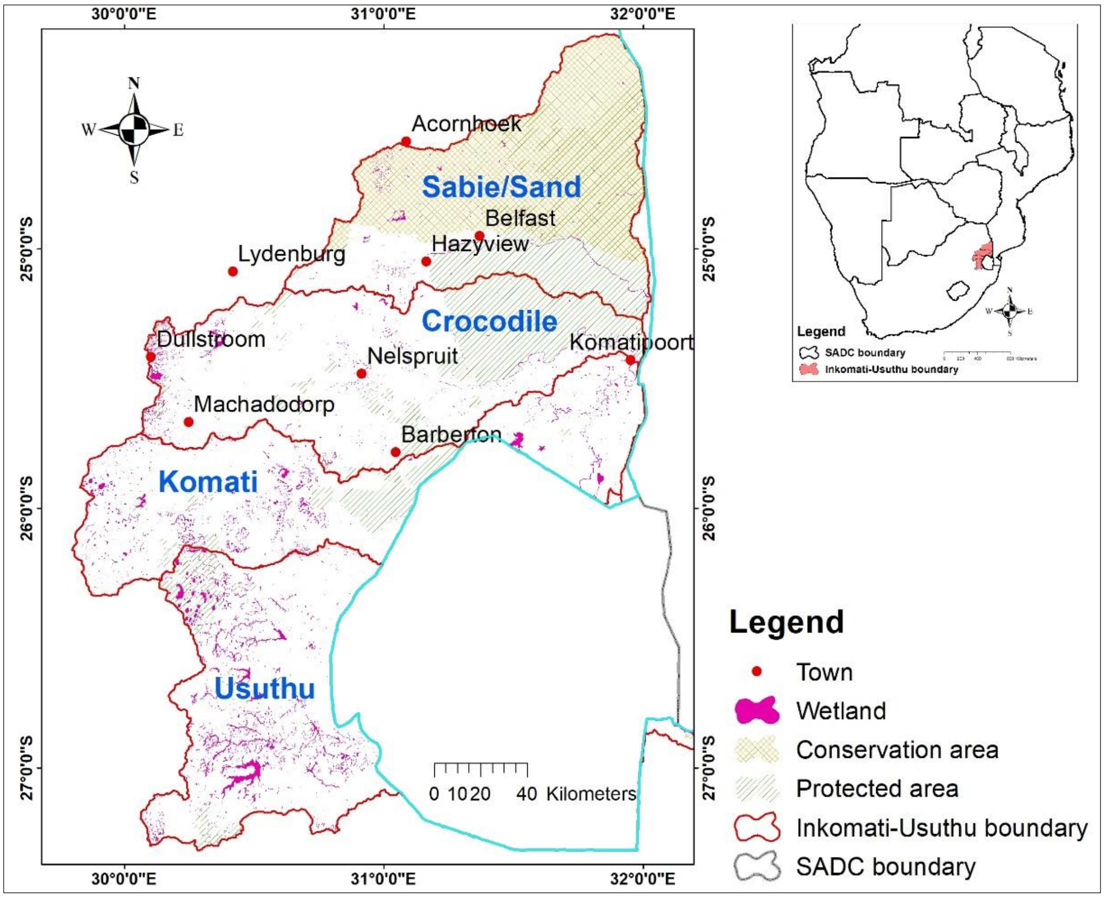


Figure 4.3. Restricted areas in the study area

4.1.2 Sensitivity analysis

The sensitivity analysis was undertaken to understand the stability and robustness of the AHP method (Gibson and Campana, 2018). Simulations of a 50% weight reduction of each criterion with equal distribution among remaining criteria predicted the system was most sensitive to landuse and least sensitive to slope. Percentage of suitable area (moderate to very high) under initial conditions equalled 92% (Table 4.2). However, a 50% reduction in land cover reduced suitable locations by 15%, whereas a 50% reduction in slope increased suitability by 3% (Table 4.2). Sensitivity results are directly related to weighting in Table 4.1.

Table 4.2. Results of sensitivity analysis with 50% reduction of each criterion with equal distribution of weight to the criteria

Criteria reduced by 50%	Proportion of suitable area in the catchment (%)
Land use/cover	77
Rainfall	88
Population density	90
Geology	81
Soil	89
Drainage density	94
Road proximity	94
Depth to groundwater	86
Slope	93
Original criteria weights	**92**

4.2 BHUNGROO IRRIGATION TECHNOLOGY AND SOLAR IRRIGATION PUMPING SUITABILITY MAPPING

4.2.1 Analytic Hierarchy Process and Weighted overlay analysis

An Analytic Hierarchy Process (AHP) was developed within a Multi-Criteria Decision Analysis to spatially delineate locations most suitable for BIT and solar irrigation pumping in the IUCMA. Similar to BIT suitability mapping, the results from the AHP weighted overlay method were expressed on a scale from 1 to 5, with 5 being very high suitability and 1 very low suitability for BIT. The criteria in order of importance based on weights included land use /cover, solar, population density, geology, soil, rainfall, drainage density, proximity to road, depth to groundwater and slope (Table 4.3). These weights were derived from the AHP matrix presented in Table 4.3.

Table 4.3. Pairwise comparison matrix for Multi-Criteria Decision Analysis.

Matrix		Landuse/cover	Soil	Geology	Slope	Rainfall	Drainage density	Road proximity	Population density	Depth to GW	Solar	Normalised principal Eigenvector (Weight)
Landuse/cover	1	1	5	5	7	5	3	3	1	7	1	26.63%
Soil	2	1/5	1	1	5	1/2	1	1	1	3	1	9.25%
Geology	3	1/5	1	1	3	1	3	1	1	1	1	9.32%
Slope	4	1/7	1/5	1/3	1	1/3	1/3	1	1/3	1	1	4.18%
Rainfall	5	1/5	2	1	3	1	1	1	1	1	1/3	8.07%
Drainage density	6	1/3	1	1/3	3	1	1	1	1	1	1	7.68%
Road proximity	7	1/3	1	1	1	1	1	1	1	1	1	7.49%
Population density	8	1	1	1	3	1	1	1	1	3	1	10.79%
Depth to GW	9	1/7	1/3	1	1	1	1	1	1/3	1	1/3	5.11%
Solar	10	1	1	1	1	3	1	1	1	3	1	11.50%

Note: GW is groundwater. Consistency ratio (CR) for this matrix was 7.4% < 10% for matrix larger than 4 by 4, hence the assigned weights and pairwise comparison matrix were consistent and acceptable (Saaty, 1980).

4.2.2 Excluded areas

The areas excluded from the analysis due to restricted use included water bodies (e.g. dams), conservation, wetlands and protected areas are shown in Figure 4.4.

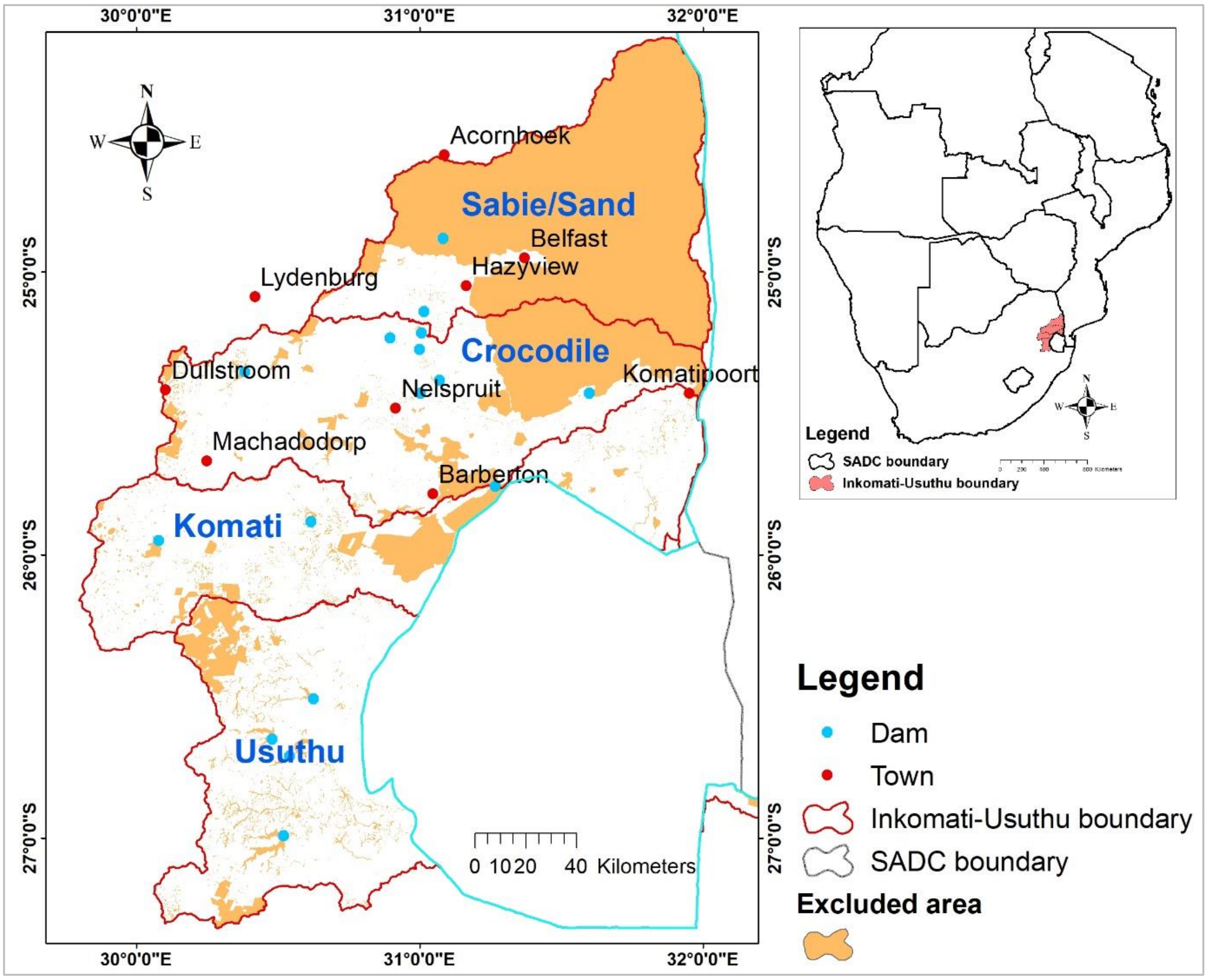


Figure 4.4. Excluded areas in the study area

4.2.3 Suitability of solar water pumping and BIT technology

The ten spatial datasets were combined to generate a suitability map (resolution of 30 m) for solar water pumping and BIT across the IUCMA (Figure 4.5). The study accounted for non-suitable or restricted areas (Figure 4.5) that included dams, wetlands, conservation and protected areas. These excluded areas accounted for about 41% (16 117 km^2) of the study area (Figure 4.6). Land areas with very high suitability for both solar pumping and BIT, accounted for 11% of the analysed land area in the IUCMA (4 241 km^2) as presented in Figure 4.5. The suitability results show area of high suitability (5 166 km^2; 13%), moderate (6 262 km^2; 16%), low (4 503 km^2; 12%), and very low (2 790 km^2; 7%). These areas are located to the west of Barberton town (Figure 4.5). The result showed that around 40% (15 669 km^2) of the area was available for both technologies with moderate to very high suitable sites.

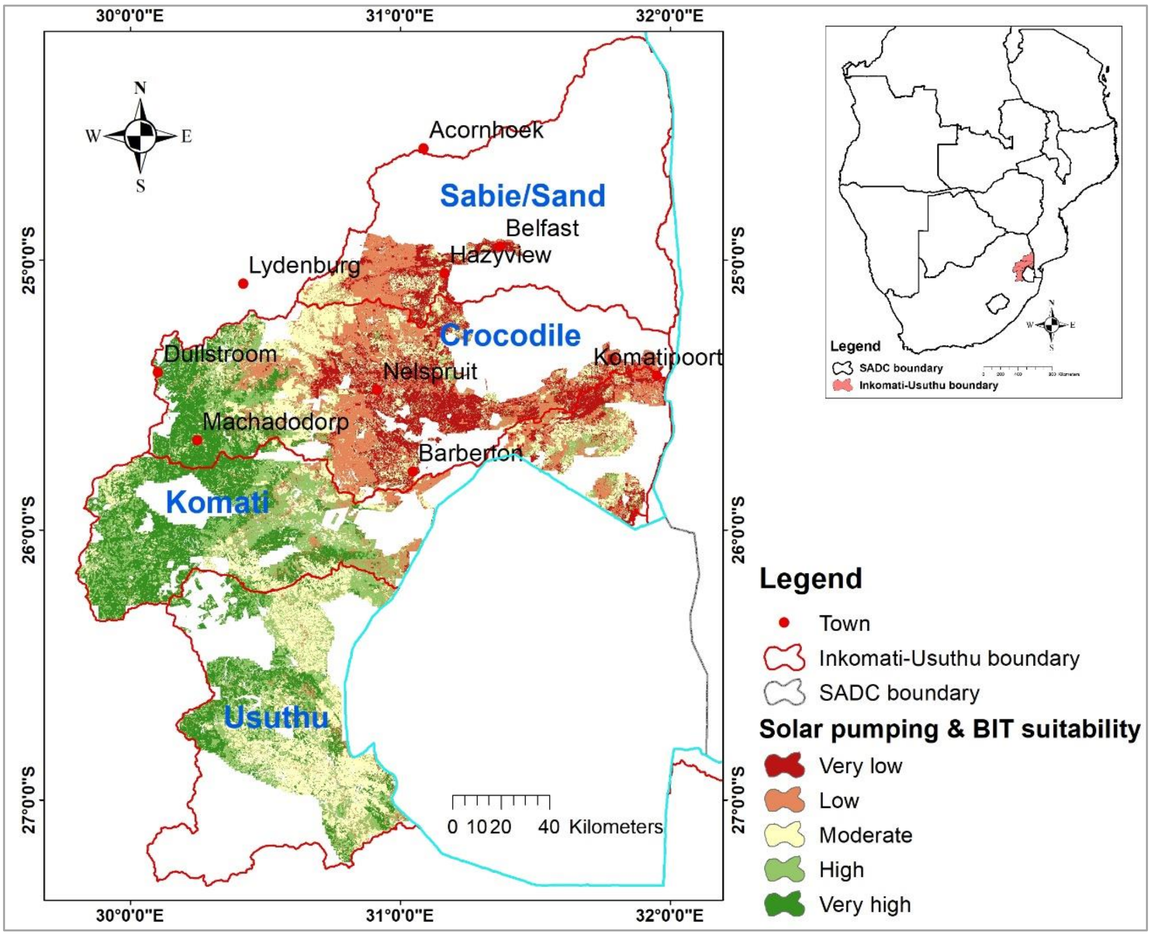


Figure 4.5. Solar pumping and Bhungroo Irrigation Technology suitability map for Inkomati-Usuthu Catchment Management Agency. White colour in the IUCMA boundary showed excluded areas**.**

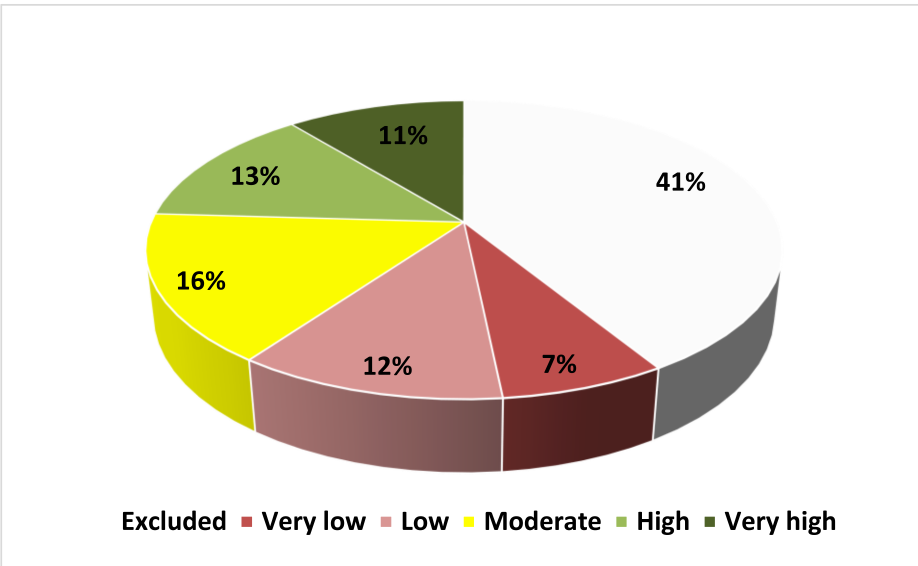


Figure 4.6. Weighted overlay results by percent of catchment area.

4.3 PERFORMANCE EVALUATION OF BIT FOR CONJUNCTIVE GROUNDWATER AND SURFACE WATER USE, COUPLED WITH SOLAR IRRIGATION PUMPING

4.3.1 Groundwater quality

The groundwater physical and chemical parameters are shown in Table 4.4 and Table 4.5, respectively. Electrical conductivity (EC), pH, salinity and temperature were directly measured in-situ after a year of Bhungroo installation and operation were acceptable for irrigation (Table 4.4). The pH values are within the target standard values of 6.5-8.4 (DWAF, 1996), and hence do not pose threat to crop production. The water quality from the Bhungroo boreholes (White River BH1 and Schoemansdal BH), before and after installation shows slight increase in some parameters (Table 4.5) such as Na, Ba, Sb, Se, As, Cr and slight decrease Mn, Fe, Cu, Zn and B, but still the concentration levels of all parameters were way below the DWAF (1996) target range levels and do not pose threat to crop production. The other parameters that increased only for Bhungroo in Schoemansdal were Al and Cl, while the ones that decreased were K, Mg, Ca, Ni and V. The other parameters that increased for White River Bhungroo (White River BH1) only are K, Mg, Ni, V, Ca and Be, while Cl decreased (Table 4.5). These results indicate that the Bhungroo performance is not negatively impacting the irrigation water quality at both sites. However, it should be noted that irrigation water quality problems to crops is often linked to the constituents that cause them and the interactions between constituents. For example, infiltration of water into the soil that is affected by both the sodium adsorption ratio and the total dissolved solids of the water. Hence, yearly monitoring of Bhungroo water quality is still essential to identify any early signs of deteriorating water quality.

Table 4.4. Average quality of physical parameters

Site	pH	Salinity (mg/ℓ)	TDS (mg/ℓ)	EC (µS/cm)	Temperature (Degree Celsius)
White River BH1	7.5	650.5	956.5	1201.5	22.7
White River BH2	7.7	639.0	936.5	1167.0	23.0
Schoemansdal BH	8.5	569.0	912.0	1141.5	23.1

TDS is Total Dissolved Solids, EC is Electrical conductivity, date of in-situ measurement, 18/08/2022.

Table 4.5. Comparison of water quality before and after Bhungroo installation with irrigation water quality standards

	Before Bhungroo installation (13/05/2021)			After Bhungroo installation (04/03/2022)			DWAF (1996)	
Parameter	**White River BH1**	**White River BH2**	**Schoemansdal**	**White River BH1**	**White River BH2**	**Schoemansdal**	**Target range**	**Maximum range**
Be (mg/ℓ)	0.00000001	0.000000005	ND	0.0001709	0.000062	ND	up to 0.1	0.1-0.5
B (mg/ℓ)	0.00000032	ND	0.0000079	ND	ND	ND	up to 0.5	0.5-6.0
Na (mg/ℓ)	14.49	14.31	9.357	15.43	17.5	10.62	up to 70	70-460
Mg (mg/ℓ)	5.84	7.318	11.36	6.317	7.124	9.858	NS	NS
Al (mg/ℓ)	ND	ND	ND	ND	ND	0.01119	up to 5	5.0-20.0
K (mg/ℓ)	1.171	1.605	1.877	1.239	1.338	1.713	NS	NS
P (mg/ℓ)	-	-	-	0.237	0.284	ND	NS	NS
Ca (mg/ℓ)	16.97	19.87	21.46	21.16	20.99	20.11	NS	NS
Ti (mg/ℓ)	0.000309	0.0002204	0.000309	-	-	-	NS	NS
V (mg/ℓ)	0.000806	0.000343	0.002475	0.00442	0.00469	0.00823	up to 0.1	0.1-1.0
Cr (mg/ℓ)	0.000056	ND	0.001248	0.00029	0.00008	0.00273	up to 0.1	0.1-1.0
Mn (mg/ℓ)	0.001014	0.01326	0.001552	0.000008	0.000007	0.000017	up to 0.02	0.02-10.0
Fe (mg/ℓ)	0.004829	0.004618	0.003998	0.0000003	ND	0.00017	up to 5.0	5.0-20.0
Co (mg/ℓ)	ND	ND	ND	0.0000078	0.000046	0.00006	up to 0.05	0.05-5.0
Ni (mg/ℓ)	0.000229	0.000679	0.001359	0.000396	0.000185	0.001304	up to 0.2	0.2-2.0
Cu (mg/ℓ)	0.00097	0.002945	0.000549	ND	ND	ND	up to 0.2	0.2-0.5
Zn (mg/ℓ)	0.00777	0.1096	0.004343	0.000083	0.000087	0.00005	up to 1.0	1.0-5.0
As (mg/ℓ)	0.000056	0.00005016	0.004254	0.00035	0.00036	0.018	up to 0.1	0.1-2.0
Se (mg/ℓ)	ND	0.0001066	0.000256	0.00055	0.00111	0.00059	up to 0.02	0.02-0.05
Rb (mg/ℓ)	0.00027	0.0006306	0.001173	-	-	-	NS	NS
Sr (mg/ℓ)	0.1445	0.2023	0.05838	-	-	-	NS	NS
Mo (mg/ℓ)	0.000047	0.00005417	0.000082	0.00063	0.00079	0.00086	up to 0.01	0.01-0.05
Pd (mg/ℓ)	0.00000012	0.0000002006	0.00000001	-	-	-	NS	NS
Ag (mg/ℓ)	0.000000002	0.000000001745	ND	-	-	-	NS	NS
Cd (mg/ℓ)	0.000000009	0.00000002044	0.00000001	0.0001952	0.0001656	0.0001871	up to 0.01	0.01-0.05
Sn (mg/ℓ)	ND	ND	ND	ND	ND	ND	NS	NS

Parameter	White River BH1	White River BH2	Schoemansdal	White River BH1	White River BH2	Schoemansdal	Target range	Maximum range
Sb (mg/ℓ)	0.00000014	0.000000123	0.00000015	0.0013	0.001193	0.001174	NS	NS
Ba (mg/ℓ)	0.0000513	0.00004124	0.00002438	0.2717	0.2342	0.1475	NS	NS
Pt (mg/ℓ)	ND	ND	ND	-	-	-	NS	NS
Au (mg/ℓ)	0.000000003	0.0000000002	ND	-	-	-	NS	NS
Hg (mg/ℓ)	ND	ND	ND	ND	ND	ND	NS	NS
Ti (mg/ℓ)	ND	ND	ND	-	-	-	NS	NS
Pb (mg/ℓ)	ND	ND	ND	ND	ND	ND	up to 0.2	0.2-2.0
Bi (mg/ℓ)	0.000000002	0.000000002	0.000000001	-	-	-	NS	NS
Th (mg/ℓ)	ND	ND	ND	-	-	-	NS	NS
U (mg/ℓ)	0.00000003	0.00000002	0.00000001	0.0003798	0.0001892	0.0001724	up to 0.01	0.01-0.10
Cl (mg/ℓ)	18.0	25.0	11.0	16.2	17.6	14.7	up to 100	100-350
F (mg/ℓ)	-	-	-	0.33	0.44	0.31	up to 2.0	2.0-15.0

Note: (-) not analysed; ND is not detected; NS is no standard reported by DWAF (1996)

4.3.2 Sodium hazard (Sodium Adsorption Ratio)

The concentration and composition of soluble salts in water determines its quality for irrigation. Two criteria used for evaluating water quality for irrigation purposes (Magdoff and van Es, 2021) used were water salinity (EC) presented above and sodium hazard (sodium adsorption ratio -SAR). The irrigation water quality before and after implementation of the Bhungroo Irrigation technology (BIT) was not negatively affected by enhanced recharge from the Bhungroo technology (Table 4.6). The irrigation water quality was classified as excellent (adjusted SAR <1) as shown in Table 4.7, based on Magdoff and van Es (2021). Even the general monitoring borehole (Whiter River BH2) showed SAR <1, indicating the water from the two Bhungroo sites is very good for irrigating all types of crops. The results are below the target standard of < 2 (DWAF, 1996). However, continued (yearly) monitoring is required to ensure the SAR remains below 2. These results indicate that the BIT filter is effective in cleaning the injected or recharged surface runoff to prevent contamination of subsurface waters. The BIT contributes to maintain the highest quality of the groundwater and protect existing and future beneficial uses of the groundwater through the reduction of the discharge of contaminants to the groundwater.

Table 4.6. Classification and management needs of irrigation water based on Sodium Adsorption Ratio

Period	**Before BIT installation**		**After BIT installation**	
Site	SAR	Adjust SAR	SAR	Adjust SAR
White River BH1	0.80	0.70	0.85	0.80
White River BH2	0.70	0.60	0.85	0.73
White River BH3	0.80	0.60	0.80	0.60
Schoemansdal BH	0.1	0.1	0.58	0.55

Table 4.7. Classification and management needs of irrigation water based on Sodium Adsorption Ratio (Magdoff and van Es, 2021**)**

Adjusted SAR	**Classification**	**Management Considerations**
< 1	Excellent	None
1-2	Good	Little concern, add pelletized gypsum periodically
2-4	Fair	Aerify soil, sand topdress, apply pelletized gypsum, monitor soil salinity
4-8	Poor	Aerify soil, sand topdress, apply pelletized gypsum, leach soil regularly, monitor soil salinity closely
8-15	Very Poor	Requires special attention; consult water quality specialist
> 15	Unacceptable	Do not use

4.3.3 Mechanism Controlling Groundwater Chemistry

A piper (trilinear) diagram (Figure 4.7) was constructed to display the relative concentrations of the different ions from individual water samples collected in the study area (Piper, 1944). Hydrochemical facies for both sites reflect the effects of chemical reactions occurring between the minerals and groundwater. The dominant water type at two sites for both dry and wet seasons was Ca-HCO_3

(Calcium bicarbonate waters) according to Sadashivaiah et al. (2008). The majority of the water samples suggest that the chemical weathering of rock-forming minerals or lithologies and related weathering processes are affecting the groundwater quality by the dissolution of rock through which water is circulating.

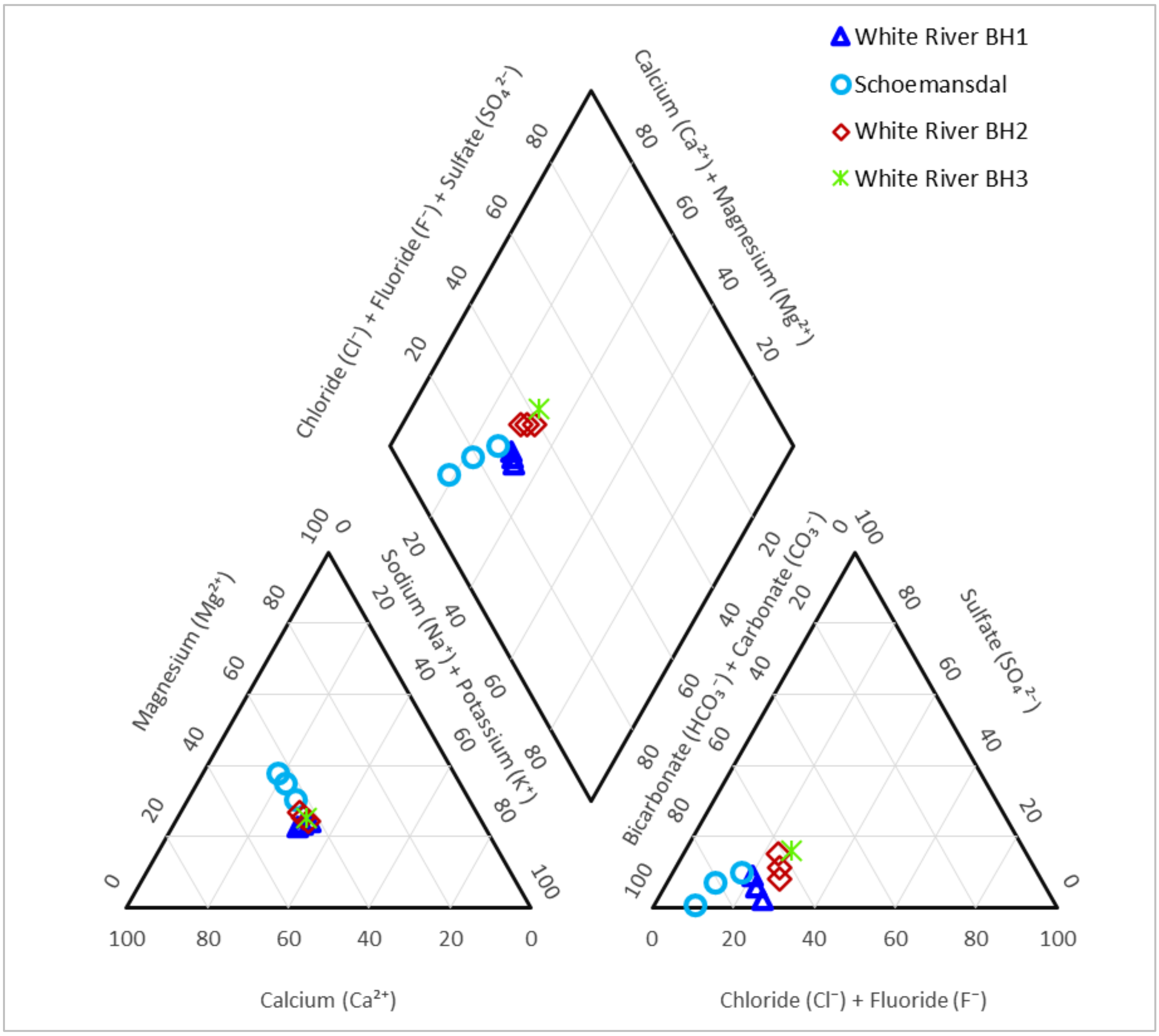


Figure 4.7. Piper diagram for White River and Schoemansdal sites for both wet and dry seasons

4.3.4 Groundwater recharge estimation

4.3.4.1 Chloride Mass Balance (CMB)

The groundwater recharge (05/2021-08/2022) at White River site ranged from 37-57 mm/a (mean 48 mm/a), while at Schoemansdal it ranged from 62-89 mm/a (mean 75 mm/a) as shown in Table 4.8. The groundwater recharge as a percentage of annual precipitation was 10% and 15% for White River and Schoemansdal Bhungroo sites, respectively. The Bhungroo therefore significantly contributes to groundwater recharge, however the analyses did not show what the areal extent of the recharge is.

Table 4.8. Average Bhungroo recharge estimation using the chloride mass balance method for 2021/2022.

Site	Cl_{BHG} (mg/ℓ)	Cl_p (mg/ℓ)	*P* (mm/a)	R_T (mm/a)	Proportion of R_T to *P* (%)
White River BH1 (*n* =5)	19.6	2	458	48	10
Schoemansdal BH (*n*=5)	13.3	2	488	75	15

Note: P is precipitation, Cl_p chloride concentration in precipitation, Cl_{gw} is chloride concentration in groundwater, Cl_{BHG} is chloride concentration of water from Bhungroo, R_T is total recharge (natural + artificial recharge through the Bhungroo borehole filter material).

4.3.5 Isotope analysis

The groundwater samples from the Bhungroos (White River – BH1 and Schoemansdal – BH) and other boreholes, White River BH2 and BH3 plotted above the Global Meteoric Water Lines (GMWL) and Inkomati rainfall (LMWL) resembling local rain events that recharge groundwater through direct recharge (no evaporation during recharge or infiltration) from high and short intense rainfall events during summer months (November to March) as shown in Figure 4.8. Further, deviation from the GMWL suggests that recharge occurs through slow accumulation of rainfall (diffused rainfall infiltration) and/ or focused recharge in depressions filled by surface runoff or as a result of topographical effects (De Vries and Simmers, 2002). To understand how much recharge occurs, the proportion of recharge water (new water) to groundwater (old water) in the Bhungroo is presented next.

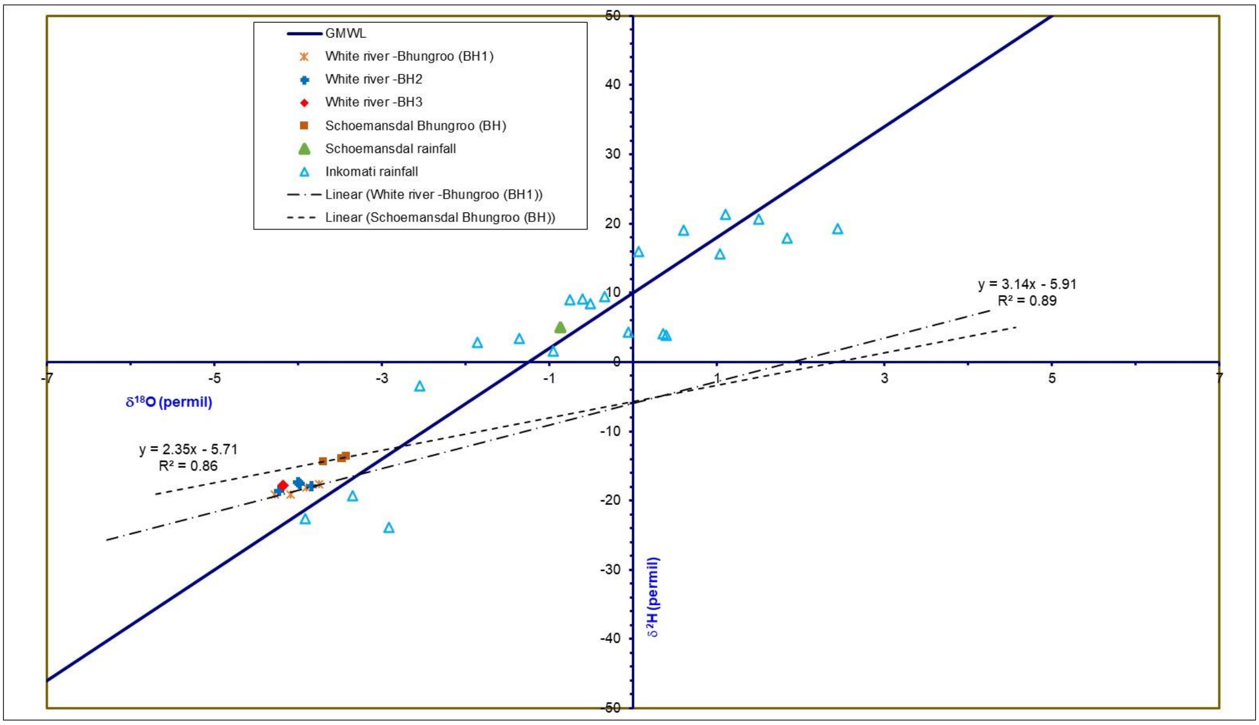


Figure 4.8. Isotope levels from groundwater and rainfall samples, with Global and Local Meteoric Water Lines from two study sites

4.3.6 Quantification of proportion of recharge to old groundwater in Bhungroo

The average proportion of recharge water to groundwater for White River was 0.07 (7%) from 18-Oxygen tracer and 0.05 (5%) from hydrogen tracer, while for Schoemansdal it was 0.19 (19%) from 18-Oxygen and 0.18 (18%) from hydrogen tracer (Table 4.9). The average recharge water in the Bhungroos was 0.06 (6%) and 0.18 (18%) for White River and Schoemansdal, respectively. This result is comparable with those from chloride mass balance of 10% and 15% for White River and Schoemansdal Bhungroos, respectively (Section 4.3.4.1).

Table 4.9. The proportion of recharge water to groundwater at the two Bhungroo sites

Bhungroo site	18-Oxygen			Estimated fractions		2-Hydrogen			Estimated fractions			
	Bhungroo water ($\delta^{18}O$‰)	Groundwater ($\delta^{18}O$‰)	Rainfall ($\delta^{18}O$‰)	Q_{GW}/Q_{BHU}	Q_{new}/Q_{BHU}	Bhungroo water ($\delta^{2}H$‰)	Groundwater ($\delta^{2}H$‰)	Rainfall ($\delta^{2}H$‰)	Q_{GW}/Q_{BHU}	Q_{new}/Q_{BHU}	Average Q_{GW}/Q_{BHU}	Average Q_{new}/Q_{BHU}
White River BH1 (*n=4*)	-3.92	-4.19	-0.47	0.93	0.07	-17.78	-19.13	-5.55	0.95	0.05	0.94	0.06
Schoemansdal BH (*n=5*)	-3.46	-4.06	-0.87	0.81	0.19	-13.85	-17.87	5.00	0.82	0.18	0.82	0.18

Note: Q_{GW}/Q_{BHU} is ratio of groundwater to total water flow from the Bhungroo; Q_{new}/Q_{BHU}; Q_{GW} is groundwater discharge; Q_{BHU} is discharge from Bhungroo borehole; Q_{new} is discharge from the recently recharged water from the Bhungroo, and is calculated by subtracting Q_{GW}/Q_{BHU} from 1; Average Q_{GW}/Q_{BHU} is the estimated average fractions from Oxygen-18 and 2-Hydrogen.

4.3.7 Estimation of groundwater age

Tritium analysis was used to estimate the time since recharge to the groundwater system occurred and the susceptibility of the groundwater system to contamination. Abiye (2013) reported tritium concentration in precipitation in South Africa to be about 3 TU. Knowing the current tritium input in precipitation in South Africa, it was possible to estimate the apparent groundwater age (Table 4.10) or residence time and to evaluate whether the recent rainfall is actually recharging the aquifers. All groundwater samples contained detectable amounts of tritium indicating the renewability of water in the Bhungroo boreholes. No detectable amount of tritium in groundwater is normally equated to no recharge or to very old water probably recharged some long time ago (groundwater residence time). Tritium values from the two sites (13/05/2021) varied from 1.0-1.9 TU (Table 4.10), indicating the aquifer is receiving recharge from recent rainfall. This makes the sites suitable for artificial recharge using the Bhungroo technology. Using a semi-quantitative approach by Clark and Fritz (1997), tritium content less than 0.8 TU indicated sub-modern waters approximately recharged before 1950s, while groundwater samples with tritium content exceeding 0.8 TU indicated a mixture of modern and sub-modern waters of recently recharged rainfall thus suggesting active recharge (Clark and Fritz, 1997). No samples had tritium values lower than 0.8 TU, suggesting that there are no sub-modern recharged waters, likely to be recharged prior to 1950s. All the groundwater samples had tritium values between 1.0-1.9 TU, which fall within the 0.8-4 TU range, classified as a mixture of modern (recently recharged water) and sub-modern recharged waters (Clark and Fritz, 1997) (Table 4.10).

Table 4.10. Groundwater tritium values and age from the study sites

Site	Date	Tritium (TU)	±Δ Tritium (TU)	Interpreted age (years)	Recharge classification
White river – BH1	13/05/2021	1.9	0.3	8.2	mixture of modern and sub-modern
White river – BH2	13/05/2021	1.4	0.3	13.7	mixture of modern and sub-modern
White river – BH3	13/05/2021	1.8	0.3	9.2	mixture of modern and sub-modern
Schoemansdal	12/05/2021	1.0	0.3	19.7	mixture of modern and sub-modern

4.3.8 Quantification of irrigation water use and energy savings

4.3.8.1 Estimation of irrigation water use

The irrigation water used per ha (Table 4.11) ranged from 5 875-9 180 m^3/ha, with an average of 6 660 m^3/ha and 7 466 m^3/ha for White River and Schoemansdal sites, respectively. These results are comparable to those reported in Western Cape (5 874 m^3/ha) and Limpopo (8 841 m^3/ha) by Bonthuys (2018). These differences can be explained by crop types in summer and winter rainfall areas, crop varieties and whether irrigation is done on a permanent or supplementary basis. Water productivity (Table 4.11) for cabbage was generally higher at Schoemansdal site (average 6.2 kg/m^3) compared to White River site (4.5 kg/m^3), but comparable to 4 kg/m^3 reported for cabbage by Le Roux et al. (2016). This may be attributed to drip irrigation system used at Schoemansdal site, while sprinkler irrigation is used at White River, with chances of increasing susceptibility to crop diseases and pests. The result indicates that there is more water applied when crops are grown on small plots compared to larger fields (0.25 ha). This calls for the need to adjust irrigation water depending on the field size and type of crop, and training of the farmers in irrigation scheduling.

The estimated water use on 40 blocks of nursery trees for 2021/2022 based on a solar pump with a discharge of 1.4 m^3/hr, irrigating 5 times per week, with each irrigation event being 1hr for one block of trees, was 14 600 m^3/yr.

4.3.8.2 Estimation of energy consumed and carbon emissions

The energy consumed and carbon-dioxide emissions by a petrol pump in Schoemansdal and an electric pump fed from the grid in White River is shown in Table 4.12. The overall electricity bill for the White River farm decreased from R9 000/month to R4 000/month after the installation of the solar irrigation pump, as a result of the Bhungroo borehole being connected to the solar power. The electricity bill could have been lower than R4 000, if the other borehole (White River BH2) was not connected to the grid.

For White River BH2 site, the 2.2 kW submersible pump powered from the grid, delivered an average of 4.5 m^3/hr, although the maximum specified is 6 m^3/hr (https://www.pumps.co.za/products/p23c21-svm-5539-2-2kw). Using the prepaid electricity tariff of R2.56/kWh (2022), the pump consumes 2.2 kW/hr and 8.8 kW/h for 4 hours of pumping (irrigation event), costing R22.53/day (City of Mbombela., 2022). This translates to 880 kWh/season for 0.25ha to (3 520 kWh/ha.season), 10 560 kWh/ha.year and costing R 27 034/ha.year for tomato crop.

Considering that every kilowatt-hour (kWh) produced, 1 kg of carbon dioxide (CO_2) is emitted from an electric pump connected to the grid, and for every litre of petrol (0.75 kg) used, 2.3 kg of CO_2 is emitted, because during combustion, carbon from the fuel combines with oxygen from air to produce CO_2 with more weight than 1 litre of petrol, weighing 0.75 kg (Eskom, 2015; IPCC, 2009). The carbon-dioxide emissions ranged from 11 261 kg/ha.yr to 35 190 kg/ha.yr for petrol pump (Schoemansdal site), while for an electric pump powered from the grid (White River site) it ranged from 8 976 kg/ha.yr to 10 560 kg/ha.yr (Table 4.12). All carbon emissions associated with water pumping are mitigated if the solar irrigation pumping is used.

Table 4.11. Quantification of irrigation water use and water productivity

Site	Crop type	Area (ha)	Irrigation time (hr)	No. of irrigation events per week	No. of weeks per season	Pump discharge (m^3/hr)	Water used (m^3/season)	Water used (m^3/ha)	Yield (kg)	Water productivity (kg/m^3)
Schoemansdal	Cabbage 2021	0.05	6	3	17	1.2	367	7 344	2 700	7.4
Schoemansdal	Cabbage 2022	0.04	6	3	17	1.2	367	9 180	1 800	4.9
Schoemansdal	Green beans	0.25	6	3	17	4.8	1 469	5 875	2 000	1.4
White River	Cabbage	0.25	4	5	17	4.5	1 530	6 120	5 400	3.5
White River	Tomato	0.25	4	5	20	4.5	1 800	7 200	2 500	1.4

Table 4.12. Quantification of energy use by fuel (petrol) and electric pumps

Site	Crop	Area (ha)	No. of irrigations per season	Carbon dioxide (CO_2) emitted per litre from petrol	Carbon dioxide (CO_2) emitted (Kg/kWh) electric pump	Fuel used (ℓ/season)	Pump energy consumed (kWh/irrigation event	Carbon dioxide from pump (Kg/ha.season)	Carbon dioxide (Kg/ha.yr)
Schoemansdal	Cabbage 2021	0.05	51	2.3	-	255	-	11 730	35 190
Schoemansdal	Cabbage 2022	0.04	51	2.3	-	255	-	14 663	43 988
Schoemansdal	Green beans	0.25	51	2.3	-	408	-	3 754	11 261
White River	Cabbage	0.25	85	-	1	-	8.8	2 992	8 976
White River	Tomato	0.25	100	-	1	-	8.8	3 520	10 560

Note: Assumed 3 growing periods per year. Irrigation events depends on the crop growing period. Tomato has the longest growing period of 140 days

4.3.9 Estimate of crop production and income from the BIT and solar irrigation pumping technology

Quantification of crop production and income from the BIT and solar irrigation pumping technology is shown in Figure 4.9-Figure 4.12, and for macadamia nut nursery in Figure 4.13. The use of solar irrigation pumping at Schoemansdal site reduced the production expenses by 42-47% compared to petrol pump, and 9-29% at White River site compared to the grid-connected pump. The reduction in expenses resulted in significant increases in gross margin ranging from 29-84% under petrol pump, and 8-73% under the grid-connected pump. This increase in gross margin was attributed to the significant costs reduction in energy used for pumping irrigation water. The energy costs from fuel pump and grid-connected pump made up 9-42% and 10-29% of production costs, respectively. The use of solar irrigation pumping can result in almost doubling of farm income because of the cheap renewable energy, while eliminating the greenhouse gas emissions associated with grid electricity and fuel pumps. A summary of the production costs, sales and gross margin per hectare is shown in Table 4.13 for easy of comparison across the two sites. The Schoemansdal site uses better crop management practices and had better market prices, as shown by higher price of cabbage sales per hectare compared White River site.

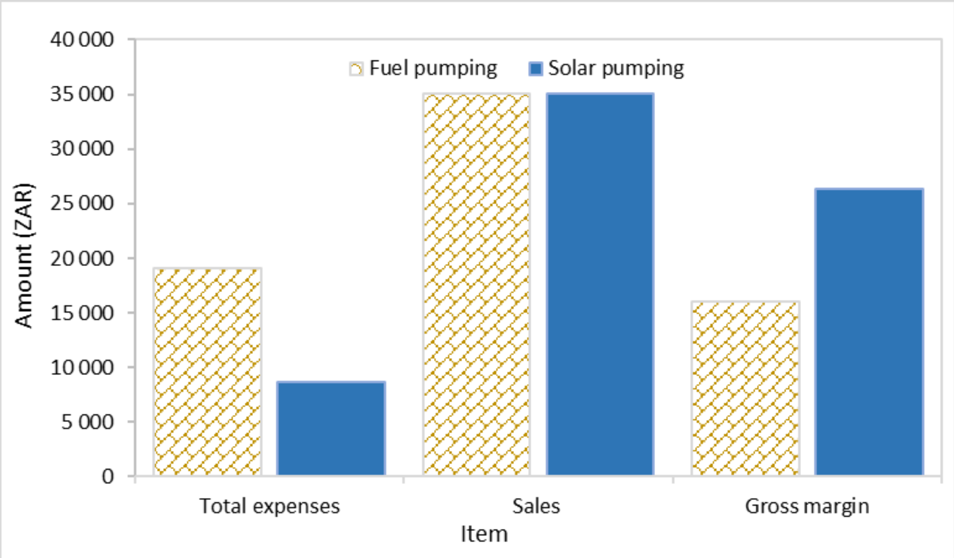


Figure 4.9. Cabbage production for 2021 on 0.05ha field size at Schoemansdal site

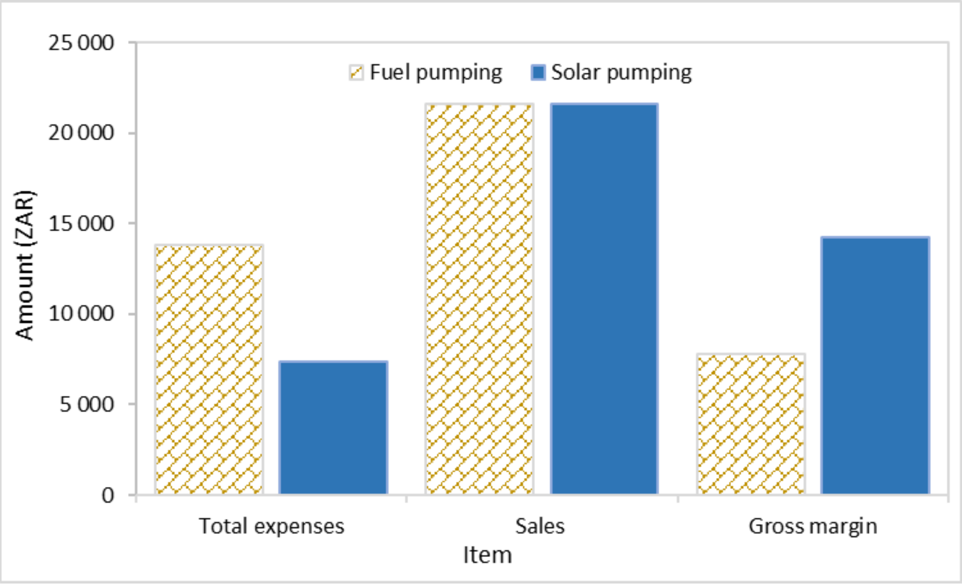


Figure 4.10. Cabbage production for 2022 in 0.04ha field size at Schoemansdal site

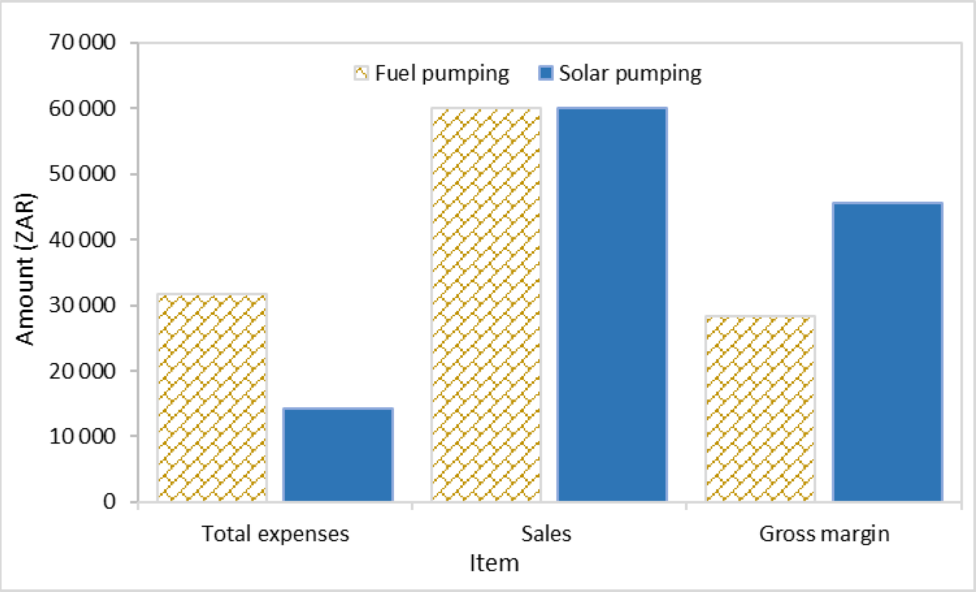


Figure 4.11. Green beans production in 2022 on 0.25ha field size at Schoemansdal site

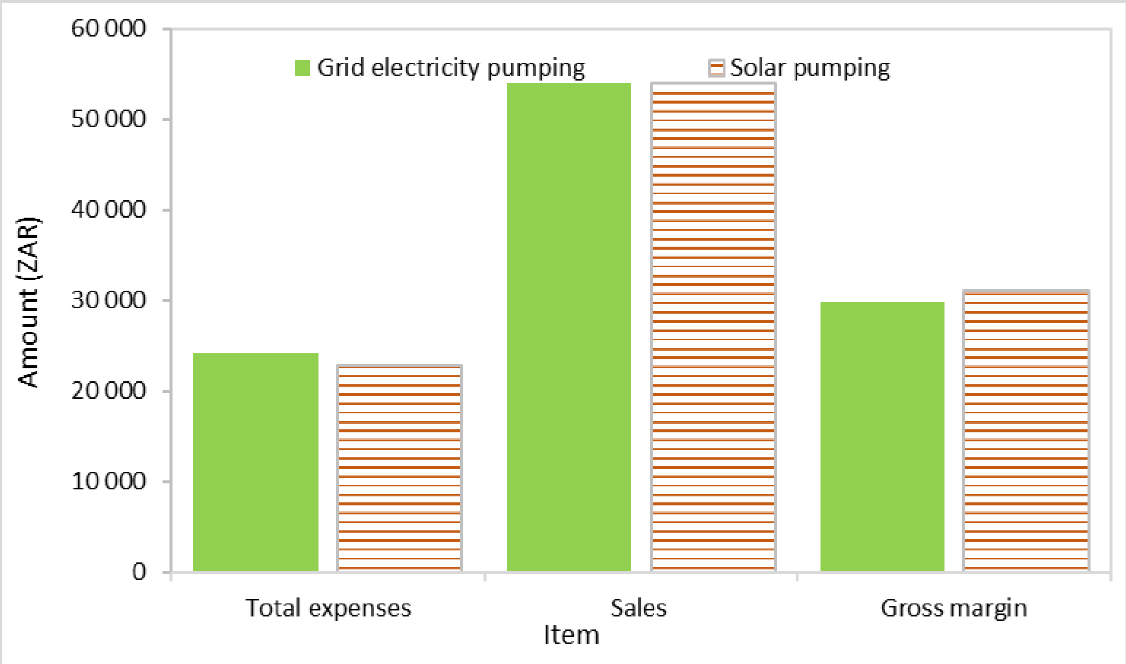


Figure 4.12. Cabbage production in 0.25ha field size at White River site in 2022

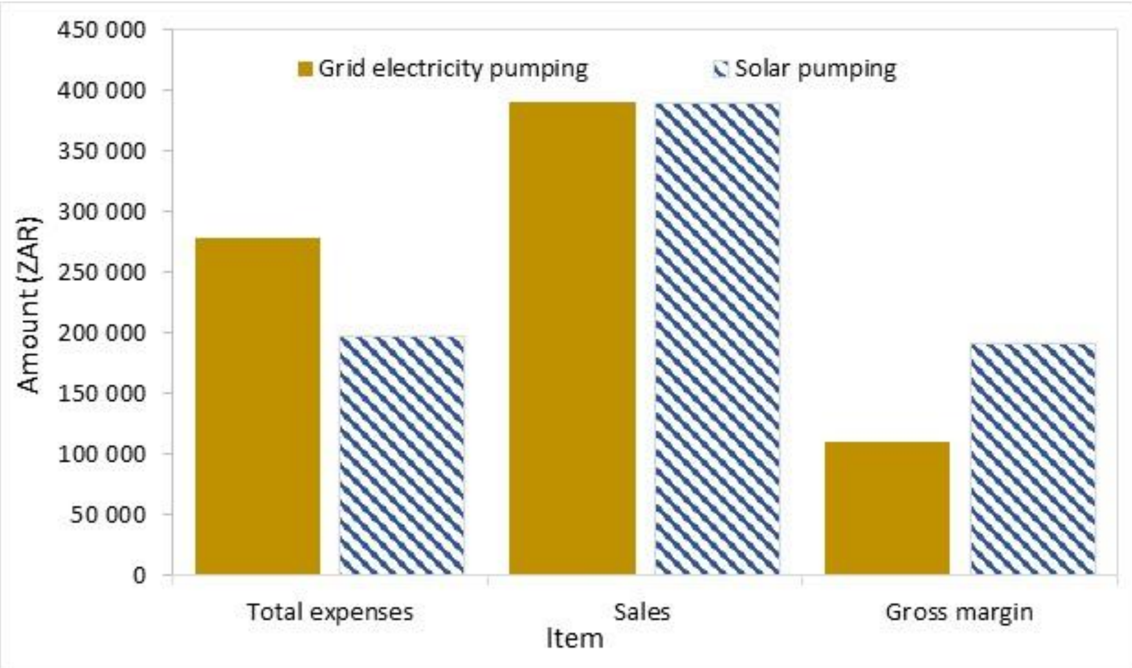


Figure 4.13. Macadamia nut nursery of 6 000 trees at White River site in 2021-2022

Table 4.13. A summary of total expenses, sales and gross margin for crop production using different energy sources

Site	Crop type	Energy type	Total expenses (R/ha)	Sales (R/ha)	Gross margin (R/ha)
Schoemansdal	Cabbage 2021	Fuel	253 625	585 000	331 375
Schoemansdal	Cabbage 2021	Solar	145 250	585 000	439 750
Schoemansdal	Cabbage 2022	Fuel	345 938	540 000	194 063
Schoemansdal	Cabbage 2022	Solar	183 375	540 000	356 625
Schoemansdal	Green beans 2022	Fuel	98 896	240 000	141 104
Schoemansdal	Green beans 2022	Solar	57 280	240 000	182 720
White River	Cabbage 2022	Grid	209 158	450 000	240 842
White River	Cabbage 2022	Solar	190 458	450 000	259 542

4.3.10 Stakeholder interviews: Barriers and Opportunities for solar irrigation pumping

This study examined the drivers as well as barriers for scaling solar powered irrigation system (SPIS) in South Africa through literature surveys, online interviews, and a physical evaluation of installed SPIS. Preliminary surveys have revealed that the adoption of solar powered irrigation system (SPIS) in South Africa is still low compared to other countries in Sub Saharan Africa (SSA).

4.3.10.1 Barriers

A summary of the barriers include:
Biophysical

- Hydrogeological characteristics and constraints
- Solar energy availability. The solar irradiation is not available for 24 hrs a day but only 8-10 hrs a day on average.
- Climate change. The decrease in rainfall results in reduced surface water and groundwater availability for irrigation, while an increase in temperature results in high crop water demand and more solar energy for pumping.

Technical

- Poor quality of solar products that results in poor performance and frequency breakdowns.
- Unavailability of net meters. Net meters are needed to enable excess solar energy generated by farmers to be fed into the grid. In India, net meters are available and farmers sale the access electricity generated to the power utility, and they get an income at the end of the month.
- Low-levels of knowledge of solar powered irrigation by users

Financial barriers

- Limited number of financing business models
- Lack of access to credit, as smallholder farmers are unbankable

Market

- Lack of access to market information on the solar products
- Unavailability of high-quality solar components

Institutional

- Government is not prioritizing solar powered irrigation.

Policy

- Governments have no capacity to certify, monitor installations and ensure safe and sound connections

4.3.10.2 Opportunities

The opportunities associated with solar irrigation pumping include:

- Diversify to high value crop production in greenhouse to save water and increase profits. Government and private sector should set-up funding for greenhouse structures
- Improve market access, and prices have to be realistic, e.g. market should determine the prices of produce
- Training of youth and farmers on solar powered irrigation installation and maintenance through farmers' day seminars at their farms
- Use contract farming model to fund solar irrigation pumping. The irrigation schemes may be supported by a private company with inputs and some equipment including solar components, and farmers grow the crops for the private company on a contract.

4.3.10.3 Challenges

The challenges of security and out-scaling the solar powered irrigation are presented next.

Security

Theft of SPIS components especially in remote rural areas remains a major risk for farmers, as the market environment for stolen solar panels in such areas is favourable. Various measures have been implemented to reduce theft, including use of portable SPIS systems which allow the indoor storage of panels during times of non-usage and provides an opportunity to be able to irrigate multiple plots, with same system. However, farmers prefer fixed systems as the transportation of panels is laborious. Other measures include fencing, security fasteners, anti-theft bolts, alarms and system monitoring tools, employment of security guards, and elevating the panels on poles and firmly welding. From a social perspective it was also found that the creation of a sense of ownership in the community where members see mutual benefits works better for safeguarding of the panels, as security of panels becomes each community member's responsibility. This approach can be complemented by appropriate incentives to help track down and recover stolen solar panels in case of a theft incident. Lastly, the decline in solar panel prices overtime, may eventually diminish their attractiveness in the informal market.

Trade-off to scaling of solar powered irrigation

Once manufactured, transported, and installed, the energy costs for lifting water and environmental costs are almost nil, except for end-of-life final disposal. This low energy costs results in farmers increasing crop intensity in a bid to maximise revenue thereby causing over-abstraction and depletion of groundwater resources, especially in regions where the water recharge rate is low. This requires the solar powered irrigation to be promoted together with improved water use technologies, such as drip and use of tools that improve irrigation water scheduling (e.g. chameleon sensors and wetting front detector) to avoid over or under irrigation.

4.4 GUIDELINES ON THE INSTALLATION AND OPERATION OF THE BHUNGROO IRRIGATION TECHNOLOGY AND SOLAR IRRIGATION PUMPING

This section presents the guidelines for the planning, designing, implementing and monitoring of artificial recharge using the Bhungroo Irrigation Technology (BIT) and solar irrigation pumping in smallholder farming.
Specifically,

- To identify source of water for recharging the Bhungroo borehole
- To install Bhungroo borehole
- To install the solar irrigation pump
- To quantify the water recovery efficiency of the BIT
- To quantify groundwater water use from BIT

The guidelines are intended for use by proponents of artificial recharge schemes, consultants, catchment water and agricultural management agencies, and local municipalities. The guidelines provide a snapshot and checks to be considered during the solar system installation, as the assumption is that the installer/supplier designs and selects appropriate solar pump and solar panels to match the water requirements and site conditions of the farm.

The installation of the BIT can be done on a new borehole or may be retrofitted to an existing borehole if conditions allow.

4.4.1 Conditions for installation of BIT

The conditions suitable for installation of BIT to be considered during planning include:

- Water shortages during the dry season from the borehole
- Suitable infiltration and percolation characteristics of vadose zone. The infiltration should not be high as the recharge water will be lost, resulting in low recovery rates of the recharged water
- Soft material around the borehole to enable manual or mechanical excavation of the filter box. A filter box or tank is a pit of know dimensions and volume that is excavated and filter material laid inside to filter or remove suspended material and other contaminates or dirty in the water recharging the aquifer.
- Suitable topographical and hydrogeological set up and sites for creating subsurface reservoir through cost effective artificial recharge techniques. Multi-criteria and GIS suitability methods (Magombeyi, 2022a) may be used at farm or catchment scale to identify suitable sites for artificial recharge and installation of BIT.
- Catchment area upstream (Box 4.1) of borehole to harvest runoff for recharge in to the filter box, or the area may be low lying and prone to flooding. In this case flood waters during the rainy season are captured by the filter box as they flow past the filter box.
- Availability of water of suitable quality to recharge the borehole or aquifer. The water available can be quantified from rainfall data, rainfall runoff analysis, or from surplus water availability, preferably unutilised component of surface water. Recharge water should be clean and free from contaminates, and should have compatibility with quality of native groundwater in aquifers
- Hydrologic and hydraulic characteristics of the aquifers such as capacity to store, transmit and yield water

- Technical feasibility
- Economic viability.

Once the site is selected, the next step is the excavation of the filter box.

Box 4.1: Catchment upstream of Bhungroo borehole for surface runoff harvesting

A T-shaped channel constructed from local material collecting surface runoff upstream and directing it to the Bhungroo filter box or filter tank.

4.4.2 Location of services near the proposed filter box site

Locate any services within close proximity to the borehole near the proposed filter box site. These services include underground electricity cables, water pipes, etc. Once services are located, their position should be clearly marked and protected, and care taken during excavation to avoid damaging them.

4.4.3 Excavation of the filter box

- Mark the dimensions of the filter box with the borehole casing within the filter box, i.e. the length (m), width (m) and depth (m).
- Dimensions (length, width and depth) of the filter box depends on the water needs or irrigation water requirements. The size of the filter box is related to how much recharge enters the Bhungroo borehole at each recharge event. The larger the filter box volume, the more the recharge. The dimensions can be adjusted depending on how easy it is to dig the filter box. For best results the following dimensions should be used (length × width × depth): 3 m × 3 m × 3 m (Blümmel et al., 2018). The minimum dimensions for significant results are (length × width × depth): 1 m × 1 m × 1 m (see Box 4.2).
- Dig the filter box manually. This can take about 2 days for 2 people digging, depending on the size of the filter box. Excavation can be done mechanically with an excavator; however, this will increase the overall cost of installation of the filter box, which may not be attractive for smallholder farmers.
- Support the sides of the excavation if the material is loose and is susceptible to collapse. Shoring, i.e. support of the wall sides with iron sheets and struts or wooden poles that cross over the filter box to hold the iron sheets. In flood prone areas or sandy areas, it is best to dig during the dry period to avoid or reduce the chances of sides of the excavation from collapsing or curving in.
- After digging to the required depth, clean and shape the walls and level the bottom of the excavation and construct the bottom concrete slab.

Box 4.2: Filter box size and recharge estimates

The filter box dimensions (length, width and depth) depends on the water needs or irrigation water requirements. In Northern Ghana, Owusu et al. (2017) estimated recharge rates through three Bhungroo boreholes from flooding at three different sites (Jagsi, Kpasenkpe and Weisi, with one well at each site. The recharge rates were 52 mm/yr at Jagsi site (filter box dimensions: 2.5 m × 2 m × 3 m, 110 mm/yr at Kpasenkpe site (filter box dimensions: 2.5 m × 2 m × 3 m) and 52 mm/yr at Weisi site (2.5 m × 2.5 m × 3 m). In another study, UNFCCC (2014) suggested that Bhungroo boreholes (filter box dimensions: 1-2.5 m × 1-2.5 m × 0.5-1 m) may add storage volume of 40 000 m^3 of flood water into aquifer, but an average stored volume of water from several Bhungroo boreholes was around 4 000 m^3, indicating potential to supply sufficient irrigation water to fields for 7 months period in Gujarat region of India. In South Africa, Magombeyi (2022b), estimated recharge rates from harvesting runoff upstream of borehole in to the filter box in Inkomati-Usuthu Catchment Management Agency at two sites: 48 mm/yr at White River site (filter box dimensions: 3 m × 2 m × 2.7 m) and 78 mm/yr at Nkomazi (Schoemansdal) site (filter box dimensions: 3 m × 2.2 m × 2 m). Maximum depths of filter box up to 5 m have been used, provided it is safe to excavate, and walls are supported to avoid collapse. Method to support walls against collapse during excavation can be found in engineering books.

It can be seen that the dimensions of filter box play a part in the amount of recharge water captured per rainfall event, but the number of recharge events are also important in the overall amount of recharge per year.

4.4.4 Bottom slab construction

The bottom slab (blinding) of thickness 50 mm can be constructed from class 10 MPa concrete. Mixture of 1:3:6 (cement: sand: aggregates) makes 10 MPa concrete (https://interior.tn/advice/what-is-the-strongest-concrete-mix-ratio/). Allow an additional 10% of required quantities for wastage. Let the slab dry for one day and then start building the walls of the filter box. The number of bricks and cement required depends on the size of the dug filter box. The bricks and mortar should be of good quality to avoid water infiltration through them.

4.4.5 Construction of filter box walls

- The walls should be constructed by a qualified builder. The wall must not allow water ingress in or out of the filter box.
- Leaking of the filter box walls result in short-circuiting of recharge water flow, which results in inadequately filtered water (dirty water) entering the filter box and recharging the Bhungroo borehole. This results in contamination of the groundwater or aquifer that negatively affects the uses of water from the borehole or aquifer.
- One layer of brick may be used for constructing the walls. In some cases where the ground is unstable and 2-brick layer wall may be constructed until half-way the height of the filter box and then change to one layer wall until to ground surface.
- The wall should protrude above the ground surface by a height approximately 3-4 bricks. Part of the wall must be above ground surface (150-200 mm) to avoid any external disturbance on the upper surface of the filter box, such as movement of upper filter material with soil erosion under turbulent flow of water or accumulation of any external material on upper surface of the filter box, such as plastic/polyester which might prohibit/slowdown the process of recharge.
- The wall may be plastered to ensure it is impermeable. However, in some instances if the walls are deemed impermeable there may be no need to plaster the walls.
- After constructing the walls, the next step is to make holes on the borehole casing, just above the bottom slab. If the Bhungroo borehole is new, a screen can be placed just above the bottom slab.

Water tight walls

The side walls of the filter box should be made up of bricks and mortar, with proper cementation so that no water can enter into the filter box from the sides. The bottom slab should be impermeable to avoid direct water entry between the brick wall and the bottom of the filter box.

4.4.6 Perforation of the borehole casing

- Perforate the casing, just above the slab surface using a cutting gridder for metal casing (e.g. 8-10 slits, each 100 mm wide) or a drilling tool for Polyvinyl chloride (PVC) casing. The perforations facilitate the entry of clean water that has been filtered throughout the whole depth of the filter box in to the aquifer or groundwater.

- After perforations are made, a mesh wire or plastic (the size that does not allow mosquito to pass through) is wrapped around the perforations and tied to avoid dirty and sand entering in to the aquifer through the perforations (see Box 4.3).
- After covering the perforations by mesh, lay the filter material inside the filter box.

Box 4.3: What material should be used to cover the openings or slots on the casing to avoid sand getting into the borehole?

- Commercially manufactured borehole screens may be used to cover the perforated borehole casing at the bottom of the filter box to restrict movement of sand through the casing and entering into the borehole. A borehole screen has V-shaped, closely spaced and uniformly distributed openings to minimize any hydraulic loss due to external forces applied on the screen.
- Avoid bimetallic or metal screens which corrodes rapidly (see photo below).
- Any borehole or well screen that is resistive to corrosion from catalysts such as water and acids can be installed, while constructing the Bhungroo borehole. PVC screen is not normally preferred because it provides limited open area that might affect rate of recharge and borehole yields, and there is always a need for maintaining strength of the perforated casing.
- Stainless steel and galvanized steel well screens are better options available in the market that are most resistive to corrosion and incrustation, with high strength.

Plastic mesh for covering perforations around the borehole casing

4.4.7 Laying of filter material in the filter box

The filter media consists of seven layers. Mark the depth of each layer on the 4 walls, so that when laying the filter material, the marks inside the walls guide the depth of each layer. A rake or shovel may be used to spread the material to the required level in the filter box. Wear a mask to avoid breathing dust as the laying of material may be associated with dust conditions. The laying of filter material starts from the bottom going up to the ground surface as presented in Box 4.3. Different sizes of concrete aggregates may be used as coarse material and stones. The order of layers starting from the slab at the bottom of the filter box are:

1. Very coarse material (big stones),

2. Small stones,
3. Activated charcoal or carbon,
4. Small stones,
5. Activated charcoal or carbon,
6. River sand, and
7. Small stones.

Water quality from the Bhungroo borehole

Installing well screen or covering the perforated casing with a fine mesh is encouraged if the Bhungroo is used for supplying drinking water, even if after a rain event. The purpose of an appropriate screen is to restrict sand movement into the well. The joints of well casing should be properly capped. No water should be allowed to enter the well except through the two charcoal or activated carbon layers (at least 0.15 m each) in the filter box or tank. The charcoal or activated carbon restricts sand movement downward in the filter box and absorbs any chemical or biological (fungal/bacterial) impurities present in the flood or surface runoff water percolating through it.

The filter material arrangements for a typical filter box are shown in Figure 4-14.

The stages involved in the construction of the filter box around a borehole are shown in Figure 4.15-Figure 4.18.

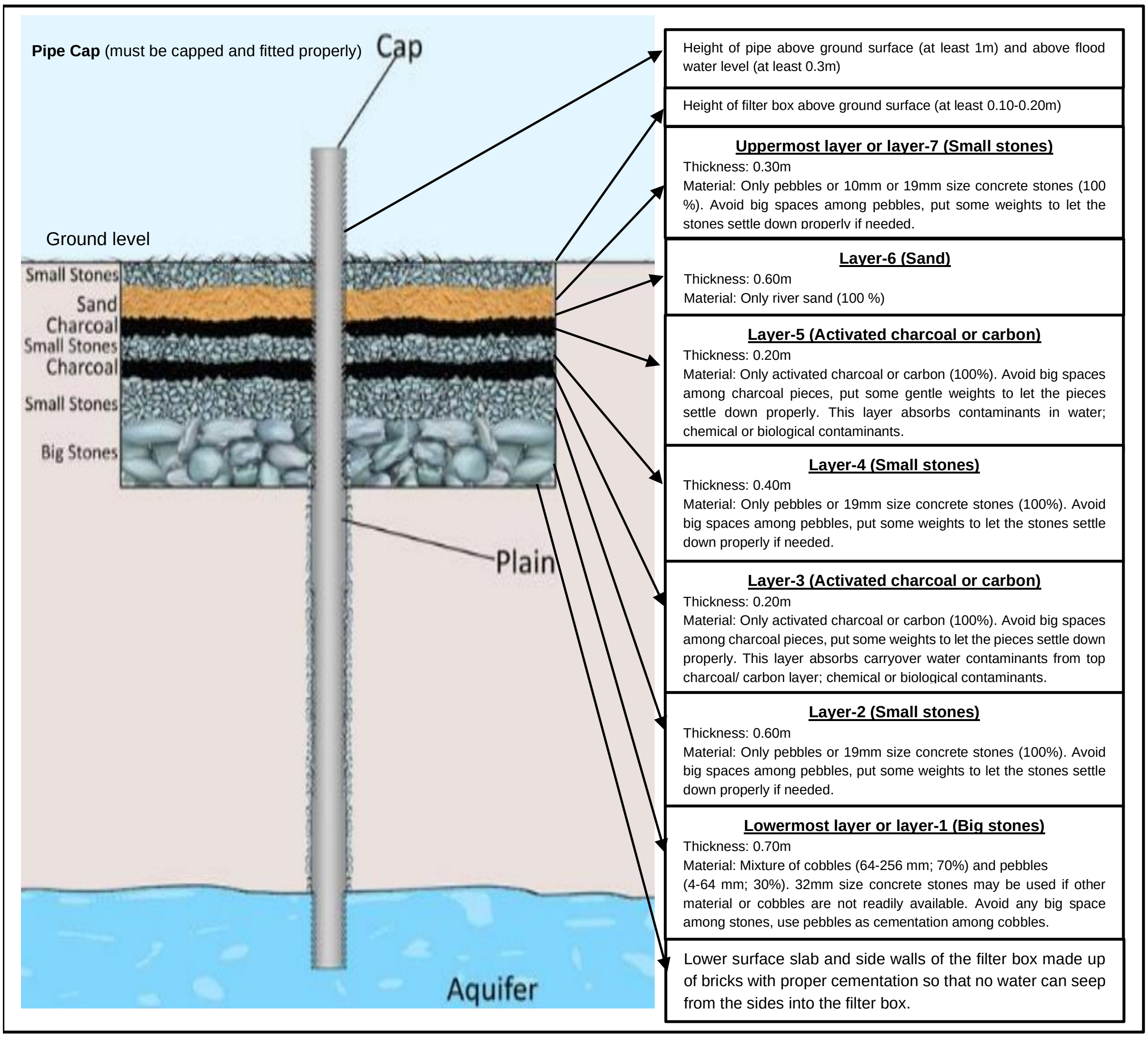


Figure 4.14. Filter material arrangement for a typical filter box
(https://pbs.twimg.com/media/EFQB49jUUAAip6e.jpg:large)

Figure 4.15. Marking the dimensions and manual excavation of the filter box

Figure 4.16. Constructed bottom slab and brick walls for the filter box

Figure 4.17. Laying of filter material, small stones and activated carbon in the filter box

Figure 4.18. Completed filter box or tank and borehole known as Bhungroo

4.4.8 Water supply to recharge the aquifer through the filter box

Water to recharge Bhungroo can be captured from flood water flowing past the filter box. In non-flooded areas the recharge water can be captured upstream of the filter box from surface runoff and channelled towards the filter box (Figure 4.18). Channel(s) or large diameter (150 mm-300 mm) pipe may be used to convey water to the filter box.

Characteristics of the channel:

- Channels should have sand traps at intervals along the path to the filter box.
- Each sand trap may be at least 0.3 m deep to reduce flow velocity for sediments to settle down.
- The channel should have 3-6 sand traps, depending on the length of the channel to capture sediments and ensure that the water getting into the filter box is free from sediments or has very little sediments.

4.4.9 Operation and maintenance: Bhungroo and solar components

The Bhungroo borehole can be pumped any time after a recharge episode as clean water is recharged in the aquifer. Suspended solids and clogging problem are common in recharge systems. A major requirement for water used in recharge projects is to be silt-free. Silt is the content of undissolved solid matter, usually measured in mg/ℓ, which settles in stagnant water with velocities which do not exceed 0.1 m/hr (MWR-CGB, 2000). Clogging occurs in two ways. First, near the surface where the interstices of the soil or filter material may be filled up and a layer of mud may be deposited on the surface. Second, suspended particles may penetrate deeper into the soil or filter material and accumulate there.

The maintenance includes:

- Cultivate plants or grass upstream of the Bhungroo borehole where runoff is generated to capture silt or sediments
- Periodically desilt the sand traps along the conveyance channel after every major rainfall event to avoid carry over of silt in to the filter box
- Scrap any silt on top of the filter box to ensure maximum infiltration and from channels transporting surface runoff water to the filter box.
- Remove any weeds that grow in the filter box
- Wipe the dust on the solar panels at regular intervals to maintain the efficiency of the panels
- Check for any loose cables and tighten them
- Check for any changes to discharge from the Bhungroo borehole. The possible causes of reduced discharge may be low water levels. If a dry-run probe is installed with the pump, it should show red colour indicating that the water levels are low. The dry-run probe is meant to protect the pump by switching it off when the water levels are low.

4.4.10 Monitoring the Bhungroo borehole

The monitoring of water levels and water quality is important in any scheme of artificial recharge of groundwater. The monitoring data speaks to the efficacy of constructed structures for artificial recharge and support effective groundwater management.

4.4.10.1 Water levels monitoring

Water levels in the vicinity of the Bhungroo borehole may be monitored, if there are existing observation boreholes or if piezometers can be easily installed. The periodic monitoring of water levels can demarcate the zone of benefit from the artificial recharge. If there is need (optional) to establish zone of benefit or influence of artificial recharge, a network of observation wells may be established in the area likely to be benefiting, and the following observations may be noticed:

- For the zone benefiting from artificial recharge, the hydrograph of water levels of the boreholes has a flat apex during the time when there is water in the recharge structure (filter box or filter tank).
- For boreholes located outside the zone of influence of artificial recharge, the hydrograph of water levels shows an angular apex for the period when the recharge is taking place.

4.4.10.2 Water quality monitoring

Water quality monitoring during the implementation of artificial recharge schemes, such as the Bhungroo technology is essential to maintain the quality standards for specified uses of the recharged resource. For example, the composition and interaction of native water in the aquifer and the recharged water is important to prevent clogging of borehole and aquifer due to precipitation of salts. Where treated wastewater is used as recharge water careful monitoring through a network of monitoring wells is required to detect and prevent any contamination. The use of this treated wastewater is described in other guidelines, and is excluded from this guideline.

Three levels of analysis can be done from collected samples:

1. Indicative: samples are collected at 1 to 4 months intervals and used to determine the presence of injected recharge water. We recommend this level of analysis during the initial stages (first year) after construction to understand the performance of the Bhungroo. The interval can be increased to 6 months as one understands more the water quality changes due to artificial recharge.
2. Basic: samples are taken at monthly intervals for boreholes already influenced by recharge to determine the effect of recharge water or runoff on groundwater quality and the purification provided by the soil and aquifer system.
3. Comprehensive: samples are taken at intervals of 6 months to 1 year from observation boreholes/wells and production boreholes to determine water quality with respect to specific standards for intended water use, in this case it's irrigation and domestic uses as farmers use water for multiple uses.

4.4.10.3 Water quality analysis before artificial recharge of the aquifer

- Take in-situ water quality parameters before construction of the Bhungroo filter box or before recharge occurs.
- Use a bailer (Figure 4.19) to collect samples if the surrounding boreholes are not equipped. Ensure that the borehole is purged before samples are taken.
- The in-situ water quality parameters may include pH, temperature, total dissolved solids (TDS), electrical conductivity (EC) and salinity.
- Take water samples from the Bhungroo borehole and any surrounding boreholes to analyse the background water quality, including pesticides used in the area.
- The water quality parameters analysed in the laboratory depends on the landuse and possible contaminants from the recharge water and farming activities or geogenic origin. These parameters may include anions (nitrate (NO_3^-), phosphorous (PO^{2-}_4), fluoride (F^-), chloride (Cl^-), sulfate (SO^{2-}_4) and alkalinity/ bicarbonate (HCO^-_3)) and cations (Aluminium (Al), Arsenic (As), Boron (B), Barium (Ba), Beryllium (Be), Calcium (Ca), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Mercury (Hg), Potassium (K), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Nickel (Ni), Lead (Pb), Antimony (Sb), Selenium (Se), Tin (Sn), Uranium (U), Vanadium (V), and Zinc (Zn)).
- The final water quality parameters selected for analysis should be within the budget.
- Take water samples from the Bhungroo borehole, any surrounding boreholes, and rainfall to analyse the stable isotopes of oxygen-18 and hydrogen-2. Ensure standard protocol for the sample collection for stable isotopes are followed, that include collection of rainfall samples soon after rainfall events to avoid exposure of the sample to sunlight before and after collection.
- Take rainfall water samples for analysis of chloride.

Figure 4.19. Water quality sampling from unequipped borehole near the Bhungroo borehole using a bailer

4.4.10.4 Water quality analysis after artificial recharge of the aquifer

Take water samples at the middle and end of wet season (after recharge) for analysis of the same parameters selected above. Also remember to take rainfall samples for chloride and stable isotope analysis as well.

The water quality analysis is used to assess the performance of the Bhungroo borehole in terms of quality and quantity of recharged water.

4.4.11 Evaluation of recharged water quality

Compare the water quality before and after artificial recharge with the local irrigation water quality standards or international standards.

- The concentration and composition of soluble salts in water determines its quality for irrigation. Two criteria used for evaluating water quality for irrigation purposes are water salinity (EC) and sodium hazard (sodium adsorption ratio -SAR) (Magdoff and van Es, 2021).
- Comment whether the water quality is within or above the local or international standards.

The fitness for use of a specific water can be categorised into different levels of acceptability and implied risk based on different indicators of water suitability. The classification system is based on a DWAF/DWS (1996) system which describes four suitability categories to which water quality can be assigned. The four categories are defined in generic terms and are applicable to any water use (Table 4.14). Suitability indictors used to assess fitness for use and establish water quality requirements or constituents that affect soil quality, crop yield and quality, as well as irrigation equipment is shown in Table 4.15.

Table 4.14. Four categories of water use quality (DWAF/DWS, 1996)

Fitness-for-use category	Description
Ideal	A water quality that would not normally impair the fitness of the water for its intended use
Acceptable	A water quality that would exhibit some impairment to the fitness of the water for its intended use
Tolerable	A water quality that would exhibit increasingly unacceptable impairment to the fitness of the water for its intended use
Unacceptable	A water quality that would exhibit unacceptable impairment to the fitness of the water for its intended use

Table 4.15. Suitability indicators to assess fitness for water use

Suitability indicators		
Soil quality	**Crop yield and quality**	**Irrigation equipment**
○ Root zone salinity ○ Soil permeability ○ Oxidisable carbon loading ○ Trace element accumulation	○ Root zone effects ○ Leaf scorching when wetted ○ Contribution to NPK removal ○ Microbial contamination ○ Qualitative crop damage by atrazine	○ Corrosion or scaling of irrigation equipment ○ Clogging of drippers

NPK: Nitrogen Phosphorous Potassium

Clogging and preferential flow routes in recharge borehole or Bhungroo

It is difficult to manage clogging in recharge boreholes and hence these systems require high water quality. Water quality can be classified based on ease of infiltration, e.g. total suspended solids >10 mg/ℓ, total organic carbon >10 mg/ℓ, and total nitrogen >10 mg/ℓ would be considered to pose a high risk of clogging (Page et al., 2020).

In reactive rock, fractured rock and karst aquifers – additional recharge could mobilise inorganic chemicals (e.g. arsenic), cause geotechnical instability, or result in rapid migration of recharge water through preferential flow routes. To understand these potential risks, groundwater sampling is undertaken to determine groundwater chemistry, geophysical logs are reviewed to clarify lithology and sampling of the soil and aquifer undertaken to determine physical and mineralogical characteristics.

In cases where water quality monitoring is impossible, the risk of contamination can be assessed based on WHO Guidelines for Drinking Water Quality sanitary survey (WHO, 2011). The survey contains three categories of questions (Page et al., 2020; WHO, 2011):

1. Hazard factors – potential sources of faecal or chemical contamination that may represent a risk to the MAR scheme (e.g. close location of a pit latrine and cow kraal in relation to a recharge or recovery well).
2. Pathway factors – potential routes of contaminants entering the source water or aquifer (e.g. leaking sewer pipes, and road).
3. Indirect factors – represents a lack of control to prevent contamination (e.g. absence of raised casing around a recharge borehole or Bhungroo may increase the risk of contamination in the event of a flood). The absence of these barriers does not lead to contamination but increase the susceptibility of the borehole or Bhungroo borehole to contamination events.

4.4.12 Assessment of water type from a Piper diagram

A Piper diagram (Piper, 1944) may be used to assess water type before and after recharge from the Bhungroo borehole, based on anions and cations composition. An example of a Piper diagram from two sites (Schoemansdal and White River) is presented in Figure 4.20.

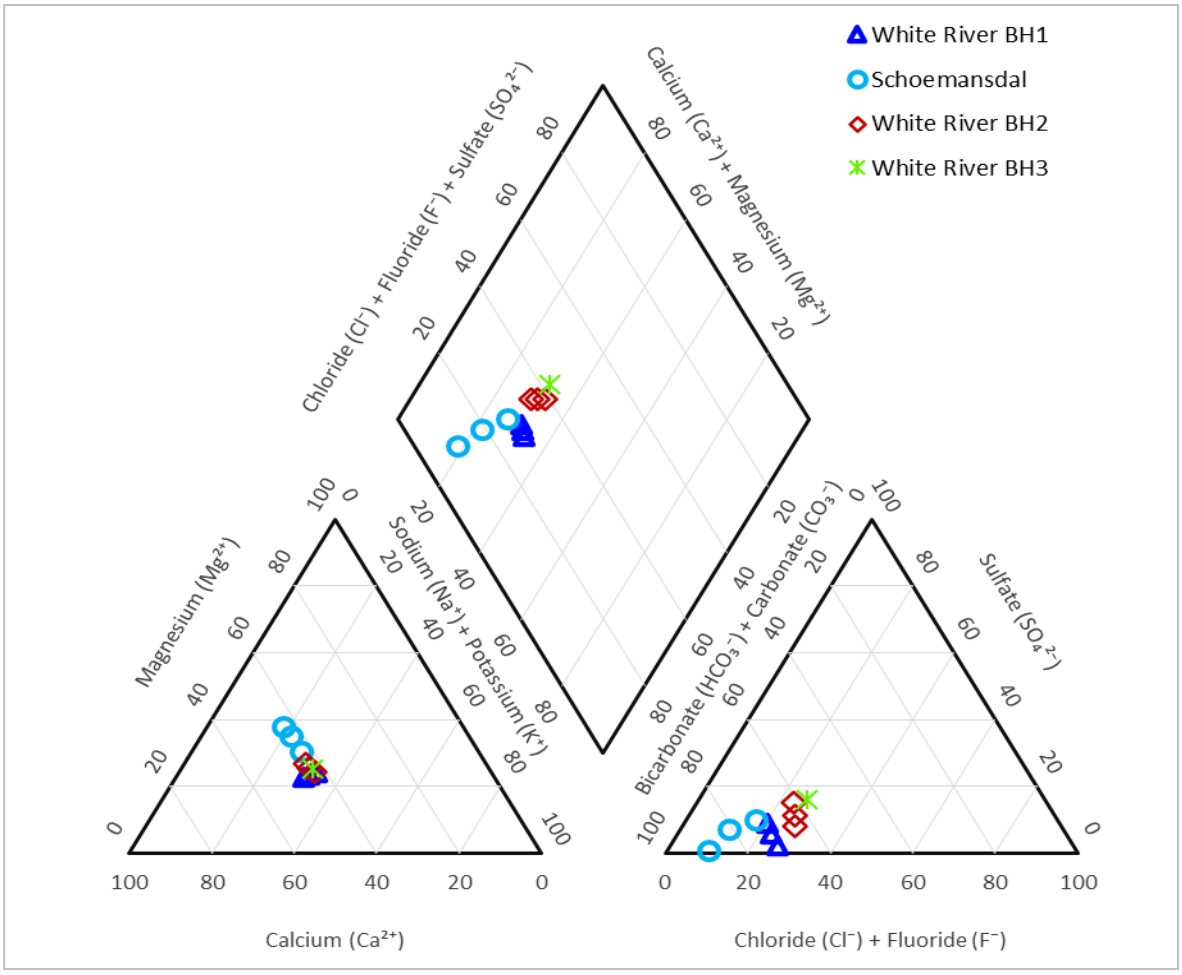


Figure 4.20. Piper diagram for White River and Schoemansdal sites for both wet and dry seasons (Magombeyi, 2022b).

4.4.13 Assessment of benefits of artificial recharge from Bhungroo technology

The impact assessment of artificial recharge schemes, such as the Bhungroo technology can be enumerated as follows:

1. Conservation and harvesting of surplus surface runoff in to groundwater reservoir which otherwise was flowing out of the catchment and finally to sea.
2. Rise in groundwater levels due to additional recharge to groundwater, and reduction in energy consumption for lifting the irrigation water from greater depths.
3. Improved and diversified cropping pattern and production in the areas using Bhungroo technology due to additional groundwater in dry periods or seasons.
4. The quality of groundwater may improve due to dilution, e.g. where native groundwater is saline.
5. Indirect benefits include reduction in soil erosion, and improved social and economic status of farmers using the Bhungroo technology due to an increased irrigation water, and crop production.

4.4.14 Recharge estimation into the Bhungroo borehole or aquifer

Recharge can be defined as “the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone” (Freeze and Cherry, 1979). The annual replenishable groundwater recharge from the Bhungroo sites includes the following components: 1) natural recharge from harvested rainfall runoff; 2) recharge through the filtration bed and borehole into the aquifer and 3) deep percolation from irrigation. In dry and hot areas, deep percolation may be minimal and may be neglected.

4.4.14.1 Estimate the recharge

Estimate the recharge from the Chloride Mass Balance method (CMB) (Naranjo, 2015). This method uses the chloride levels from the Bhungroo borehole or groundwater, and rainfall and rainfall amount when the chloride sample is collected. The amount of rainfall can be measured by a manual rain gauge.

CMB may be used to estimate natural and artificial groundwater recharge using Equation 5.

$$R = \frac{Cl_P}{Cl_{gw}} * P \qquad [5]$$

Where *R* (mm/yr) is recharge flux, *P* is average annual precipitation (mm/yr), Cl_P (mg/ℓ) the weighted-average chloride concentration in precipitation, Cl_{gw} (mg/ℓ) is the average chloride concentration in groundwater.

Estimation of runoff that recharges the Bhungroo borehole is presented next.

4.4.15 Assessment of the proportion of artificial recharge water to the native water in the Bhungroo borehole

4.4.15.1 To quantify the water recovery efficiency of the BIT

To understand how much of the infiltrated water is recovered for irrigation, an isotope tracer study is conducted. Based on the different signatures of the groundwater, surface runoff water and pumped irrigation water, an estimate of the proportion of the different water sources from the abstracted irrigation water (mixture of recently recharged and ambient groundwater) from Bhungroo borehole during the season is estimated from a simple mass balance (recovery efficiency). The stable isotopes of deuterium and oxygen-18 may be used.
A two-component mixing equation (Katz et al., 1998) can be used to estimate the relative amount of runoff water in the Bhungroo. Hence, the fraction of runoff (surface) water (F_{SW}) in the Bhungroo is defined by Equation 7:

$$F_{SW} = \frac{C_{BHGwell} - C_{gw}}{C_{sw} - C_{gw}} \quad [7]$$

Where, $C_{BHGwell}$ is the concentration of the tracers in the Bhungroo borehole, C_{gw} is the concentration of the tracers in groundwater and C_{sw} is the concentration of the tracers in surface water recharging the Bhungroo borehole.

For example, using stable isotope values of injected water and groundwater from Bhungroo borehole, the percent of injected water can be estimated using Equation 8 represented as follows:

$$F_{SW} = \frac{\delta_{BHGwell} - \delta_{gw}}{\delta_{sw} - \delta_{gw}} \quad [8]$$

Where, F_{SW} is as defined above, $\delta_{BHGWell}$ is the δ value of the Bhungroo borehole water (mixed); δ_{SW} is the δ value of the source water; and δ_{gw} is the δ value of native or ambient groundwater.

High differences in concentrations of the constituents in surface water, Bhungroo borehole and groundwater result in relatively high precision for detecting the mixing proportions of surface water in groundwater.

To lift the water from the Bhungroo borehole, a solar pump should be installed. The water can be pumped directly to the field or to a storage and then channelled to the field by gravity.

4.4.15.2 Example: Quantification of proportion of recharge to native/old groundwater in the Bhungroo borehole

The average proportion of recharge water to native groundwater can be estimated from the stable isotope analysis (using Equations 1-3 above) from samples taken before and after recharge. An example of an assessment of the proportion of recharge water to native groundwater for two sites, White River and Schoemansdal is presented in Table 4.16. The proportion of recharge water to native groundwater for White River was 0.07 (7%) from 18-Oxygen tracer and 0.05 (5%) from hydrogen tracer, while for Schoemansdal it was 0.19 (19%) from 18-Oxygen and 0.18 (18%) from hydrogen tracer

(Table 4.16). The average recharge water from isotope analysis in the Bhungroos was 0.06 (6%) and 0.18 (18%) for White River and Schoemansdal, respectively.

Table 4.16. The proportion of recharge water to groundwater at the two Bhungroo sites

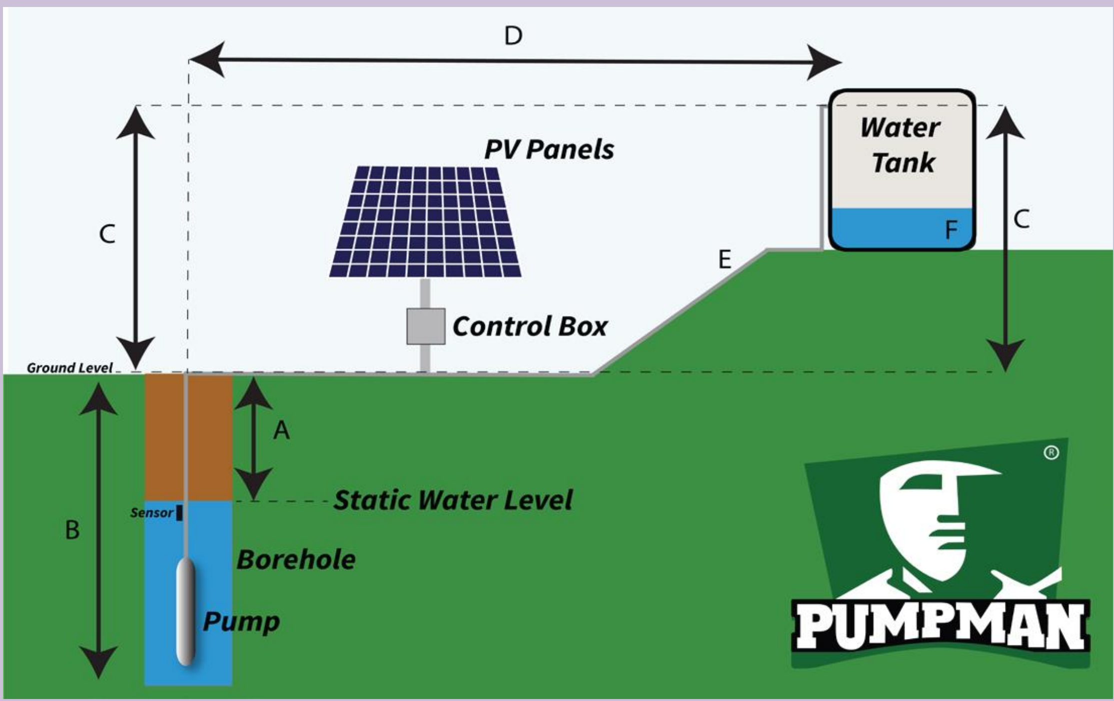
Bhungroo site	**18-Oxygen**			**Estimated fractions**		**2-Hydrogen**			**Estimated fractions**			
	Bhungroo water ($\delta^{18}O$‰)	Groundwater ($\delta^{18}O$‰)	Rainfall ($\delta^{18}O$‰)	Q_{GW}/Q_{BHU}	Q_{new}/Q_{BHU}	Bhungroo water ($\delta^{2}H$‰)	Groundwater ($\delta^{2}H$‰)	Rainfall ($\delta^{2}H$‰)	Q_{GW}/Q_{BHU}	Q_{new}/Q_{BHU}	Average Q_{GW}/Q_{BHU}	Average Q_{new}/Q_{BHU}
White River BH1 (*n=4*)	-3.92	-4.19	-0.47	0.93	0.07	-17.78	-19.13	-5.55	0.95	0.05	0.94	0.06
Schoemansdal BH (*n=5*)	-3.46	-4.06	-0.87	0.81	0.19	-13.85	-17.87	5.00	0.82	0.18	0.82	0.18

Q_{GW}/Q_{BHU} is ratio of groundwater to total water flow from the Bhungroo; Q_{new}/Q_{BHU}; Q_{GW} is groundwater discharge; Q_{BHU} is discharge from Bhungroo borehole; Q_{new} is discharge from the recently recharged water from the Bhungroo, and is calculated by subtracting Q_{GW}/Q_{BHU} from 1; Average Q_{GW}/Q_{BHU} is the estimated average fractions from Oxygen-18 and 2-Hydrogen.

4.4.16 Installation of solar pump to pump water from the Bhungroo borehole

- Go to a certified solar pump installer/supplier and inquire about the solar pump that you can buy to match your farm or irrigation water requirements.
- Rather store water in a large and raised tank than storing energy in a battery for water supply during low or no sun energy periods. Batteries are expensive (World Bank, 2018).
- There are two different types of pumps based on the electricity current used. The alternating current (AC) (Figure 4.21) and direct current (DC) pumps (Figure 4.22). The Multiflow is an AC/DC pump that uses an inverter and can use sun, grid and generator depending on the situation.
- Collect the data in Box 4.4 prior to going to a pump installer/supplier, or the pump installer may visit the site prior to giving a quotation for a suitable pump. In many cases the pump installer can also be the supplier.

Box 4.4: Information required for the design or selection of a suitable pump



A - Static water level in your borehole? .... metres (Important! See image above*)*
B - Total depth of the borehole? .... metres
C - How high are you lifting the water? .... metres (height from ground level to tank or highest point in the field, if pumping directly to the field)
D - How far do you pump from the borehole to tank? .... metres (or distance to the furthest point in the field, if pumping directly to the field)
E - Diameter of pipe used? .... mm
F - How much water do you need per day? .... litres
G - Which town is closest to you? ....
Design month with lowest solar radiation

Note: The pump size and solar panel arrays are designed based on the borehole yield, amount of water required per day and the month with least solar energy is used, e.g. July in southern hemisphere. This design ensures that if water demand is met during the worst solar energy month, then water demand is satisfied for all the other months.

Source: Cedar pumps (2022)

Borehole water yield and borehole diameter

Borehole yield is the sustainable volume of water or discharge that can be abstracted from a borehole without excessive drop in groundwater levels. For newly drilled boreholes request the driller during drilling for blow yield (ℓ/s). If the borehole was drilled already, do a borehole yield test if the resources are available. This might take the form of a 12-hr pumping test, or 24-hr pumping test to determine the yield of the borehole. This testing requires experienced personnel and can be sourced from the borehole drilling companies.

Diameter of the borehole may range from 100-200 mm.

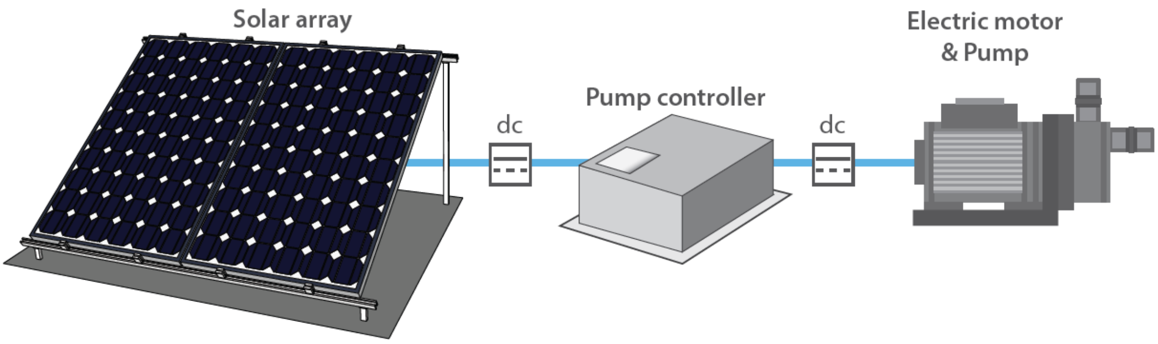


Figure 4.21. Direct Current (DC) powered pump (Cedar pumps, 2022)

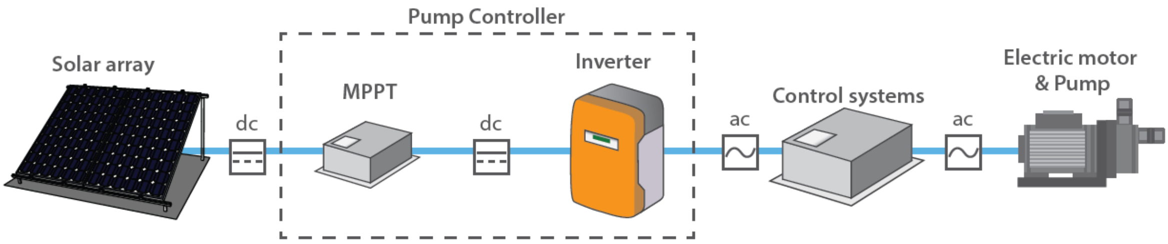


Figure 4.22. Alternating Current (AC) powered pump (Cedar pumps, 2022)

- The "pump controller" in the DC powered pump system may include a maximum power point tracker (MPPT) to ensure that the solar array is delivering power at its peak power point. The solar array may also be fixed.
- The "pump controller" in an AC powered pump system may include an MPPT as well as a DC to AC inverter in order to operate the AC electric motor which is part of the water pump. In larger systems these should be three-phase inverters to operate three-phase motors.

4.4.17 Type of Water Pump Systems

Three types of solar water pumping systems are available including:

- Borehole/well (submersible) pumps;
- Surface pumps and
- Floating pumps.

4.4.18 Installation of the solar water pumping system

- The installation of the solar pumping system should be performed safely and according to the manufacturer's instructions by a licensed electrician or similarly qualified person, as many of the larger water pumping systems operate in excess of 120V DC.
- Many solar pump manufacturers/suppliers offer complete packaged systems including the wires/cables between the array, pump controller and water pump so that electrically, the system is just a plug and play type system. In these systems it is only the water pipe and associated fittings, along with any material required for the array frame installation that need to be supplied by the system installer.
- Though the electrical wiring may be supplied there are still some key principles for working with solar electricity that needs to be understood by the system installer.

4.4.19 Array frame structure installation

Solar water pumping systems are typically provided with an array mounting frame, either for pole mounting or fixed on the ground or on the roof. Location of the pump does not necessarily have to be near a building, but it should be noted that the further the pump is from the panels the higher the loss of current in the electrical cable powering the pump. A thicker cable may be used to reduce electrical current loss.

The support frame may be made of galvanised steel, aluminium or chemically treated wood to prevent rotting. The array mounting frames must be wind rated in accordance with relevant wind loading standards in the country of installation. Installation of footings, posts, screws and/or in-ground fasteners shall follow manufacturer's instructions and associated installation manuals.

If the array is mounted on a roof, then the installer shall follow the relevant installation requirements as detailed in the two guidelines:

- Grid Connected PV Systems-Installation Guidelines (https://www.ppa.org.fj/wp-content/uploads/2019/08/Grid-Connected-PV-Systems-Installation-Guidelines-V4-250719.pdf)
- OFF Grid PV Power Systems-Installation Guidelines (https://www.ppa.org.fj/wp-content/uploads/2019/08/Off-Grid-Install-Guidelines_V3.1-July-2019.pdf)
-

4.4.20 Maintenance of solar modules/panels and pump

The maintenance of solar modules and pump are presented in Box 4.5.

Box 4.5: Maintenance of solar modules and pump (IWMI, 2022; PPA and SEIAPI, 2019)

Carry out regular maintenance on the system to prevent failure of the water supply due to an unexpected system breakdown. The following generic tips are recommended for carrying out maintenance. However, in some cases the manufacturer may require additional specific procedures to be carried out.

Solar arrays and modules:

- Clean modules (regularly as required)
- Check array structure for loose mounting connections
- Check inter-module cables and other cables for mechanical damage
- If the pump controller includes a data readout, check the array output voltage and current and compare to what would be expected under the existing conditions.

Pump controller:

- Keep the unit clean and minimize the possibility of accumulation of dust. Clean when required
- Ensure the unit is not "invaded" by insects
- Ensure all electrical connections are kept clean and tight
- Follow manufacturers recommendations.

Pumps:

- Follow manufacturer's recommendations.
- Check for unusual sounds

Cables and Pipes

- Check that there is no visible damage

4.4.21 Quantification of groundwater use from BIT

- Collect data on the pump discharge per hour, number of irrigation events per week, duration of each irrigation event, number of weeks per season, and the size of the field (ha).
- Pump discharge can be estimated by timing the time the pump takes to fill a container of known volume, e.g. time to fill a 20-litre container. An average of 6 readings may be used for final discharge calculations. Pump discharge is 20 ℓ divided by average time to fill a 20 ℓ container in seconds (ℓ/s). The discharge may then be expressed in m^3/hr.
- Calculate the water use per unit field area (ha) by multiplying pump discharge by duration of each irrigation event, multiply by number of irrigation events per season, then divide by field size (ha).
- The water use may be expressed in m^3/ha.season and m^3/ha.year, based on the number of seasons or growing periods in a year, e.g. there might be 3 growing periods or seasons in a year for vegetables.
- Measure and record the crop yield (kg) per season for each crop that is being irrigated from the Bhungroo
- For each crop calculate the water productivity (kg/m^3) by dividing crop yield (kg) by the total volume of water supplied to a particular field size (ha). If there was a rainfall event during the growing season, add the contribution of rainfall to the total irrigation water supplied, to get the total water input.

Example of irrigation water use estimation

The water used in 40 blocks of nursery trees for 2021 based on solar pump discharge of 1.4 m^3/hr, irrigating 5 times per week, with each irrigation event being 1hr for one block of trees, is 14 600 m^3/yr.

[1.4 m^3/hr ×1hr × 5 times per week × 52 weeks in a year × 40 blocks = 14560 m^3/yr]

4.4.22 Quantification of energy and carbon dioxide emitted from pumping irrigation water

4.4.22.1 Energy

Energy consumed by an electric pump (e.g. 2.2 kW submersible pump) is given by multiplying pump size (kW) by number of hours per irrigation event. For example, if the irrigation event is 2 hrs and the submersible pump size is 2.2 kW, the energy consumed by the pump is 4.4 kWh per irrigation event of 2hrs. The energy consumed per season is given by multiplying energy consumed per irrigation event by the number of irrigation events per season. The yearly energy consumption values are calculated by multiplying seasonal values by the number of growing periods per year.

4.4.22.2 Carbon dioxide emitted or mitigated

Estimation of carbon dioxide emitted or mitigated is presented in Box 4.6, while Box 4.7 gives an example of how energy and carbon emissions can be calculated.

Box 4.6: Quantification of carbon-dioxide emitted or mitigated

The carbon-dioxide emitted from a grid-connected pump is estimated, considering that every kilowatt-hour (kWh) produced, 1 kg of carbon dioxide (CO_2) is emitted, 1.4 litres of water is used, and 0.37 g of particulate emissions are released in the atmosphere (de la Rue du Can et al., 2019; Eskom, 2015). This value may change based on the source of grid electricity.

The carbon dioxide emitted from a grid-connected electricity pump can be estimated from the number of pumping hours per season multiplied by emissions per hour. Carbon dioxide emissions per year can be estimated by multiplying seasonal emissions by the number of seasons per year.

When the grid-connected pump is replaced by a solar pump, the carbon-dioxide emitted in the above calculation is avoided or reduced. This is an advantage of solar pump of reducing greenhouse gases compared to grid-connected electricity pumps.

Box 4.7: Example of energy consumed and carbon emissions

Estimation of the energy consumed and carbon-dioxide emissions by a petrol pump in Schoemansdal and an electric pump connected to the grid in White River (Magombeyi, 2022b).

For White River BH2 site, the 2.2 kW submersible pump powered from the grid, delivered an average of 4.5 m^3/hr to a 0.25 ha field, although the maximum specified discharge is 6 m^3/hr (https://www.pumps.co.za/products/p23c21-svm-5539-2-2kw). Using the prepaid electricity tariff of R2.56/kWh (2022), the pump consumes 2.2 kW/h and 8.8 kW/h for 4 hours of pumping (irrigation event), costing R22.53/day (City of Mbombela., 2022). This translates to 880 kWh/season for 0.25ha to (3 520 kWh/ha.season), 10 560 kWh/ha.year and costing R 27 034/ha.year for tomato crop.

The overall electricity bill for the White River farm reduced from R9 000/month to R4 000/month after the installation of the solar irrigation pump, as a result of the Bhungroo borehole being connected to the solar power. The electricity bill could have been lower than R4 000/month, if the other borehole (White River BH2) was not connected to the grid.

Considering that every kilowatt-hour (kWh) produced, 1 kg of carbon dioxide (CO_2) is emitted from an electric pump connected to the grid, and for every litre of petrol (0.75 kg) used, 2.3 kg of CO_2 is emitted, because during combustion carbon from the fuel combines with oxygen from air to produce CO_2 with more weight than 1 ℓ of petrol, weighing 0.75 kg (Eskom, 2015; IPCC, 2009).

An irrigated plot of 0.05 ha was irrigated by a petrol pump that consumed 5 ℓ of fuel for 6 hrs of irrigation per day, and the frequency of irrigation was 3 times per week, for 17 weeks for a crop growing cycle. Assuming there are 3 crop cycles per year, the carbon-dioxide emissions are estimated at 35 190 kg/ha.yr for the petrol pump.
Calculation:
[(5 ℓ × 2.3 kg CO_2/ℓ × 3 irrigation events per week ×17 weeks × 3 crop cycles per year)/0.05ha]
= 35 190 kg/ha.yr

Emissions from an electric-powered pump connected to the grid are calculated the same way considering that every kilowatt-hour (kWh) produced, 1 kg of carbon dioxide (CO_2) is emitted. The carbon dioxide emissions vary with the crop water demands and pumping period. All carbon emissions associated with water pumping are mitigated if the solar irrigation pumping is used.

4.5 DISCUSSION

4.5.1 Suitability mapping for MAR injection method in the form of Bhungroo Irrigation Technology

Storing surplus water during times of high availability in wet season is one of the key recommendations to mitigate groundwater and crop production vulnerability to climate change. The results showed a large proportion (92%) of area suitable for BIT implementation in the IUCMA. While the BIT should not be put in nature reserves or protected areas, it can be argued that the MAR would provide an opportunity for additional storage features in natural areas to support lower lying water access points outside of the reserves. Benefits were reported from a single BIT reported in India, that drained a 2 ha waterlogged field and supplied irrigation water for 8-12 ha field (CA, 2015). However, these benefits vary from site to site, but could contribute towards increased income and poverty reduction in farming communities. Owusu et al. (2017b) reported a net income of $5 000 to $10 000 from a single Bhungroo technology supporting an 8-ha field farmed by eight families each farming 1 ha. The ASR was reported in Netherlands for domestic water supply (Stuyfzand and Doomen, 2004), and in Australia for irrigation purposes (Murray, 2008) and in South Africa for domestic water supply.

The ranking and weighting of the criteria was comparable to Owusu et al. (2017), based on expert knowledge and the significantly high weight of 31% for the surface criteria (land use/cover) means that land cover was largely influential in the overall suitability outcome. The socio-economic criteria were also important for the successful implementation of BIT, to ensure acceptability of the technology, e.g. the technology should not be located in densely populated areas. Densely populated areas and intensified agricultural areas that apply a lot of agro-chemicals pose threat to recharge water quality and may be far from fields. We used constraints, such as excluding wetlands, conservation and protected areas in the suitability assessment to minimise the likelihood of overestimating the suitability potential for BIT.

There are reported challenges to the wider use of ASR systems, including potential contamination to groundwater, but proper siting and effective management of ASR can help reduce them (Jurgens et al., 2008). There was no data on water quality, which could be used to improve the usability of recharge water or assess the interaction of recharge water with ambient groundwater quality in the current study. The water quality data can be collected at sites selected for implementing BIT.

Validation is one of the limitations of BIT suitability maps. Hence, field validation is required to make final decision for BIT implementation. A few studies have tried to validate their results, and this was mainly restricted to comparing the maps to existing MAR sites. Jana et al. (2019) argued that improved validation of the maps can only be reached by comparison to field measurements or by re-evaluation of MAR projects that were built within the mapped area.

4.5.2 Bhungroo Irrigation technology and Solar irrigation pumping suitability mapping

There is high potential for solar irrigation from groundwater in SSA, with vast untapped solar energy and groundwater resources that provide a major opportunity to enable more widespread solar water pumping and BIT adoption. The results showed a large proportion (40%) of area in the IUCMA that is suitable for solar water pumping and BIT implementation. When solar water pumping is used in combination with the BIT technology more benefits are realised from the reduced pumping costs and the clean energy from the sunshine.

Aside from uncertainty associated with input maps, the second aspect affecting uncertainty is the reclassification and weighting of the different factors. A pairwise comparison was applied to improve model consistency according to Saaty (1977) and to reduce the model uncertainty. In this study, the main purpose was to evaluate where irradiation criteria of the solar pump types were met and where groundwater through BIT would be sufficiently available.

There are reported challenges to the wider use BIT systems (Owusu et al., 2017b) including potential contamination to groundwater, but proper siting and effective management of BIT can help reduce them. Availability of water quality data can be used to improve the usability of recharge water or assess the interaction of recharge water with ambient groundwater quality in the current study. The water quality data can be collected at sites selected for implementing BIT, as done in this study. Different funding models that include subsidies from the government and private sector can be used to fund the smallholder solar water pumping and BIT, with improved market systems.

4.5.3 Performance evaluation of BIT for conjunctive groundwater and surface water use, coupled with solar irrigation pumping

The BIT and solar irrigation technology package or bundle was implemented successful at the two sites. The success was evaluated by increased groundwater storage and recovery for irrigation of crops, use of environmentally friendly solar powered pumps that reduced or eliminated the use of grid electricity and fuel, reduced production expenses and increased farm income. No water quality issues were observed at the two sites in the IUCMA. The evaluation of water quality before and after BIT installation showed that some parameter concentrations decreased and a few slightly increased. However, no water quality parameters were above the DWAF (1996) target irrigation water standards. Suggesting that the BIT is unlikely to negatively impact the crop production and groundwater quality in the long-term.

The use of storage together with the BIT and solar irrigation pumping (standalone configuration, without batteries) helped to smoothen the water supply to the crops to increase production. Hybrid systems with multiple sources of energy can be used at farm. Solar irrigation pumping system works in parallel with electricity grid and/or fuel (e.g. petrol) pump to supplement solar power when the system is not producing the required amount of energy or water.

Despite these successful results, there is risk of groundwater over abstraction. The use of solar irrigation system may result in excess water withdrawal due to the zero or minimal operational costs nature of the systems, hence there is need to implement a technology bundle with improved irrigation water use efficiency such as irrigation methods, monitoring water use and groundwater levels and management. For example, changing surface and sprinkler irrigation to drip irrigation.

The cost of installing the BIT and solar irrigation pumping may be beyond the reach of many smallholder farmers, but the benefits are huge, especially under climate change. Hence there is need for Agriculture banks and microfinance institutions to work in partnership with farmer cooperatives to offer credit lines for BIT and solar powered irrigation technology bundle, and offer different options for loan prerequisites and repayments. For example, harvest cycle repayments and other Pay-As-You-Go arrangements. This increases affordability of technology bundle by giving farmers a way to cover the initial capital costs over a longer period. Considering the capital costs of installing BIT and solar irrigation pumps, and estimated income realised from different crops, the farmers can repay the capital costs in the first year at two sites under study. Government may consider careful structured subsidy for solar-powered irrigation in rural arid areas. For example, in Mexico farmers received up to 70% subsidy (GIZ and FAO, 2015).

4.5.4 Guidelines on the installation and operation of the Bhungroo Irrigation Technology (BIT) and solar irrigation

Improved sustainability of water resources for agriculture and irrigation is urgently needed in dry or groundwater depleted areas in many countries where productivity is limited by access to water. Managed Aquifer Recharge (MAR) is still an underutilized tool for water management which can be effectively used to replenish groundwater supplies (Page et al., 2020). However, from legislation point of view, the general environmental duty on all persons undertaking an activity that pollutes is to take all practicable measures to prevent or minimise any resulting human and, environmental harm (Environment Protection Authority, 2004; DWAF, 1996).

The reduced rainfall results in an increase in dry days that provide more solar energy to lift or transport irrigation water. To increase irrigation water availability and access at low energy costs during the dry season or periods, artificial aquifer recharge through Bhungroo Irrigation Technology (BIT) and solar irrigation pumping has been successfully applied at two sites in the Inkomati-Usuthu Catchment Agency, in White River and Schoemansdal in Mpumalanga Province in South Africa. Following this success, general guidelines on construction, operation and maintenance, and monitoring were developed to ensure appropriate implementation of this bundled technology (artificial recharge and solar water pumping) to other dry areas and regions, in such a way as to cause no-harm to both humans and the environment. The monitoring data speaks to the efficacy of constructed structures for artificial recharge and solar water pumping, to support effective management.

Monitoring is key and data and information collection should be standardized and collected on a common national database, making it more effective and improving coordination between different users and institutions. Uncertainties associated with technical limitations, especially related to aquifer hydrogeology, water quality, clogging, potential for third party impacts (e.g. neighbouring groundwater users), and achievability of recharge and recovery volumes, are some of the risks that need to be managed. A participatory and coordinated approach to MAR with water user groups and catchment forums, water service providers, catchment management agency at a basin or subbasin level to secure sustainable groundwater levels may address some of the uncertainties.

The success of the bundled technology (BIT and solar powered pumps) may be evaluated by increased groundwater storage and recovery for irrigation of crops, reduced or eliminated use of grid-electricity and fuel, reduced production expenses and increased farm income. The cost of installing the BIT and solar irrigation pumping may be beyond the reach of many smallholder farmers, hence the need for Agriculture banks and microfinance institutions to work in partnership with farmer cooperatives to offer credit lines for investing in BIT and solar powered irrigation technology bundle, as mentioned above.

CHAPTER 5: CONCLUSIONS & RECOMMENDATIONS

5.1 SUITABILITY MAPPING FOR MAR INJECTION METHOD IN THE FORM OF BHUNGROO IRRIGATION TECHNOLOGY

The use of suitability mapping hold substantial potential to targeting areas suitable for successful BIT implementation in semi-arid areas of Africa. The suitability mapping serves as an efficient visual tool to raise awareness on the wide applicability of MAR in the form of BIT and encourage decision-makers to consider BIT for developing water management strategies, especially for smallholder farmers. With successful implementation of BIT, irrigation water supply could be increased resulting in smallholder farmers growing multiple crops per year beyond the rainy season and improved crop yield, and crop water productivity, thereby achieving food security and rural development.

The accuracy of the suitability mapping depends on the input data quality including resolution. The limitation faced was the overall quality of the data inputs, which was a mixture of low (1 000 m × 1 000 m) and high (20 m × 20 m) resolution data. Improved data quality is recommended for future work. As such, the findings from this study provided a preliminary assessment that should be complemented and validated by field data prior to field installation.

The results from this study will be extended to include solar site suitability assessment to identify sites that are suitable for BIT and have potential for solar energy. This ensures that solar pumps can be used for irrigation water abstraction from the BIT to reduce pumping costs and increase water access to the smallholder farmers.

5.2 BHUNGROO IRRIGATION TECHNOLOGY AND SOLAR IRRIGATION PUMPING SUITABILITY MAPPING

The use of suitability mapping hold substantial potential technical requirements to targeting areas suitable for successful solar water pumping and BIT implementation in semi-arid areas of Africa. With successful implementation of solar pumping and BIT, irrigated water supply could be increased resulting in smallholder farmers growing multiple crops per year beyond the rainy season, reduced pumping costs and emissions and improved crop yield, and crop water productivity, thereby achieving food security and rural sustainable development as envisioned by United Nations (2015).

This project contributed to the Water-Energy-Food nexus by increasing renewable water resources through aquifer storage (BIT), increasing crop productivity and food security in irrigation, using clean and renewable energy from solar power generation and driving rural economic development for improved livelihoods. The findings from this study provided a preliminary assessment that should be complemented and validated by field data prior to field installation.

The results from this study extended BIT suitability mapping from the deliverable 1 with the requirements for solar water pumping site suitability assessment to identify sites that are suitable for BIT and have potential for solar energy use. The use of solar pumps to abstract irrigation water from the BIT reduces pumping costs and increase water access to the smallholder farmers.

5.3 PERFORMANCE EVALUATION OF BIT FOR CONJUNCTIVE GROUNDWATER AND SURFACE WATER USE, COUPLED WITH SOLAR IRRIGATION PUMPING

Seasonal rainfall provides opportunities to boost groundwater storage through managed aquifer recharge (MAR), yet experience with MAR combined with solar irrigation pumping is absent in the region. In response, this study provides the first known field study over 2 years on MAR using the Bhungroo Irrigation technology (BIT), and solar irrigation pumping in South Africa, Southern Africa. Two farm-scale pilots were implemented in collaboration with local farmers, whereby runoff from land upstream Bhungroo boreholes was harvested to recharge Bhungroo boreholes. The pilot sites were closely monitored over two years.

- Field data and insights on MAR are provided with respect to the quantity and quality of water, and economics from crop production.
- No water quality issues from samples collected before and after BIT installation were observed when the irrigation water was evaluated against South African irrigation water standards. Irrigation water quality is key to maintain the productivity of irrigated agricultural land and associated water resources in line with principles of integrated catchment management.
- The BIT owned and operated by both male and female farmers provides a promising approach for climate change adaptation for smallholder farmers, in both off-grid and on-grid areas.
- The water recovery efficiency was estimated at 6% and 18% for White River and Schoemansdal sites, respectively. This recovery will improve with an increase in rainfall and improved water harvesting channels on the ground surface.

5.4 GUIDELINES ON THE INSTALLATION AND OPERATION OF THE BHUNGROO IRRIGATION TECHNOLOGY (BIT) AND SOLAR IRRIGATION

Managed aquifer recharge (MAR) technologies such as the Bhungroo Irrigation Technology (BIT) provides a variety of water resources management benefits by increasing the volume of stored water and improving water quality through natural aquifer and designed filter box treatment processes. This study provides the first known field guidelines on MAR using the BIT, and solar irrigation pumping. These newly developed guidelines are a step forward towards advancing the regional MAR plans suitable for smallholder farmers and reducing some of the uncertainties surrounding the implementation and regulation of MAR projects in the form of BIT used to support irrigated agriculture.
However, these guidelines need to be complemented by other efforts, including:

- Promotion of the collection, exchange and analysis of information related to MAR in the form of BIT to allow evaluation at regional scale. This information should include economic, social and environmental viability
- Build trust in BIT and solar irrigation pumping through the development and dissemination of successful demonstration projects. This provides visual and hands on experiences to potential users by seeing a functional BIT project.

5.5 POLICY IMPLICATIONS

- Promote appropriately designed solar irrigation pumping equipment in suitable conditions to increase water access and crop production for smallholder farmers
- Establish smallholder farmer solar irrigation pumping committees with women as leaders and improving extension and technical services

- Raise smallholder crop diversification levels and move to high value crops (e.g. tomatoes, cabbages) to mitigate risk of a single crop failure and this should be aligned to market access
- However, the above policies have their limitations as the farmers need to save money to invest in solar irrigation infrastructure and access to markets to sell their produce at good prices.
- Create awareness of technology and benefits, and provide more training to build capacity of farmers and private sector to install and manage solar powered irrigation. Government can leverage grassroot structures such as extension workers, as well as cooperatives and savings club to deliver information and increase awareness on the benefits of solar irrigation pumping. Given the high cost of awareness and capacity building campaigns, spatial populated rural sites the government and development partners should lead these campaigns.
- Consider significantly reducing the overall cost of the pumps, making them more affordable to farmers by introducing tax exempt or breaks to solar generation components like solar panels, solar pumps and other modern off-grid energy products. These tax exemptions have been implemented in countries that include in Ethiopia, Uganda, Rwanda, and Zimbabwe.
- Implement market protection strategy through certification scheme for solar powered irrigation system suppliers and installers to enhance consumer confidence in solar products and exclude non-qualified suppliers and installers in the market.

5.6 RECOMMENDATIONS

Areas of further study include:

- Expansion of an evaluation of BIT and solar irrigation pumping performance and estimation of payback time from different business models in other provinces, such as the Limpopo Province.
- Assessment of different repayment or business models that include repayments after every harvest and pay-as-you-go arrangements to increase affordability of the technology bundle (BIT and solar irrigation) to farmers based on farmer resource typology.
- Develop a database to determine current spatial coverage of solar irrigation (in hectares) and operating status in South Africa to measure the adoption rate.

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APPENDIX A: FIELD INSTALLATIONS AND MONITORING

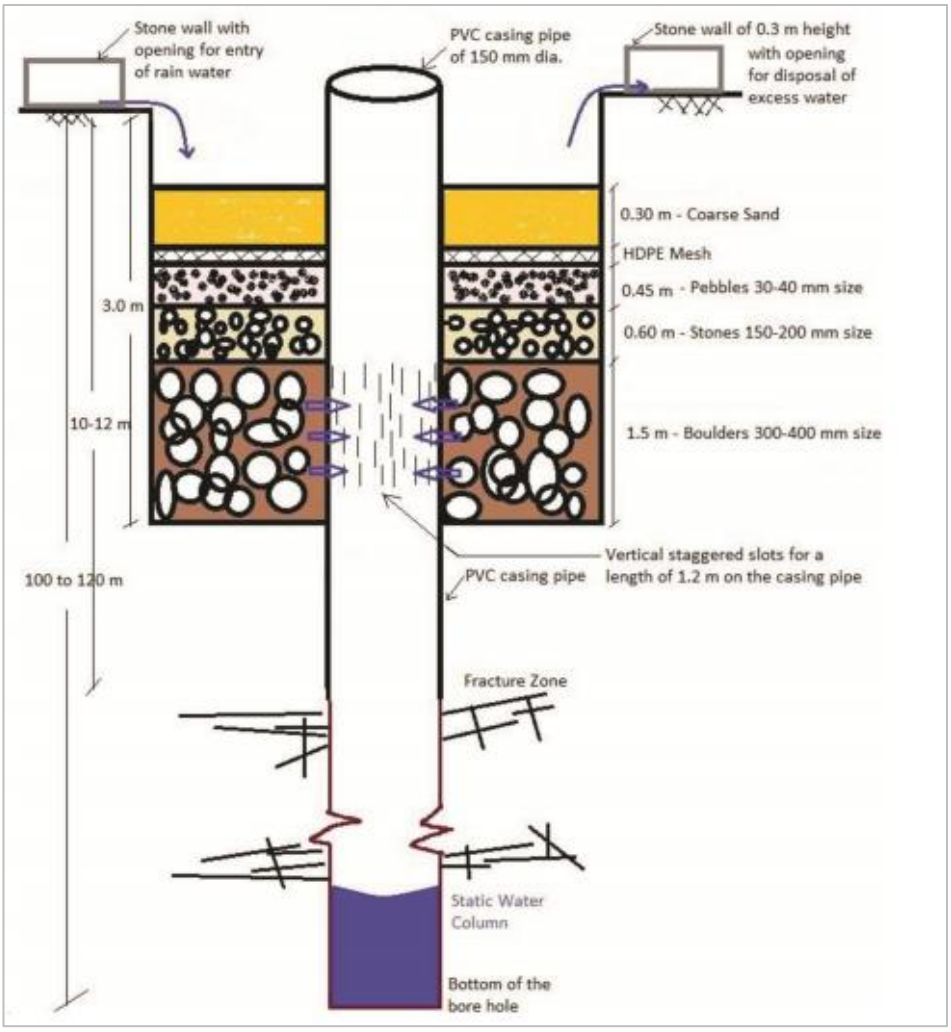

Figure A1. Typical cross-section through a recharge well such as the Bhungroo borehole.

Figure A2: Groundwater sampling using a bailer and water level measurement at one of the unequipped boreholes in White River (White River – BH3) in 2021.

Figure A3: Placing of river sand in the filter box with extended borehole casing at Schoemansdal site

Figure A4: Completed filter box for the Bhungroo borehole at White River site

APPENDIX B: STAKEHOLDER QUESTIONNAIRE

SOLAR POWERED IRRIGATION SYSTEMS (SPIS)

Personal information

Respondent name: ______________________ Contact Number:__________________________

Name of institution:_____________________ Location: ____________________________

Position:_____________________ Specialty area: ___________________

Stakeholder group: Farmer/ Supplier or installer/ Academic/ Policy-maker/ Donor____

Technical information

	Question	Answer
1.	How many years of solar pump/panel business experience do you have in Southern Africa?	
2.	How many pumps have you sold in the last 10 years?	
3.	Where have you sold the pumps? (Country, province, local area)?	
4.	Who are your major clients/buyers (percentage) – farmers or investors, governments, NGOs/donors?	
5.	Who are your main competitors in the country/region and what do you see as your main competitive advantage(s)?	
6.	What is the common size range for your solar pumps and panels in kW?	
7.	What make(s) or brand name(s) of solar systems do you deal with?	
8.	If you deal with various makes and models of pumps and panels, which make and models of solar pumps/panels are most popular in different buyer category?	
9.	Has the cost of Solar pumps come down in the last 10 years in Africa? Give a reason for your answer.	
10.	Give an example of price variations for a specific solar pump system that have been observed in the past 10 years?	
11.	What is the length of warranty period of your products?	
12.	What are the major barriers in expanding the market for solar pump/panel products?	
13.	Are there any cultural (social) barriers related to expansion of solar irrigation?	
14.	What business models are being applied or considered in overcoming financial barriers/risks to smallholders	

15.	Can you share data or other information on number of installations or other relevant indicators in specific geographies	
	Questions for Policy-makers/government institutions	
16.	What is the main policy objective that solar pumps sector can support.	
17.	What are the priority geographies or demographic groups targeted for solar powered irrigation technologies and why have they been chosen?	
18.	What is the current status of adoption solar irrigation in your region?	
19.	Do you have any specific policies related to solar powered irrigation systems (provide copy if possible)	
20.	Who are the key players who translate policies into implementation?	
21.	What incentives are provided to encourage adoptions and how sustainable & inclusive is this?	
22.	Schemes, partnerships, programs supporting solar irrigation?	
23.	Which areas of your region are gaining traction for solar powered irrigation?	
24.	Does SPIS expansion present any threat to natural resources, especially small rivers and groundwater resources? If yes, specify them.	
25.	Have you experienced any social/cultural/gender barriers in expansion of solar irrigation? How and by whom can these be addressed?	
26.	Are you aware of any short courses that relate to solar powered irrigation (e.g. Solar power installations). If yes, provide details (who offers training, length of course, enrolments, etc.)	
27.	For farmers using the solar pumps: How did you acquire your solar powered irrigation system? (self-funded, got bank loan, donor funded, government sponsored, etc.). For how much was the system installed and when?	
28.	What is the capacity of your solar powered irrigation system in terms of (i) wattage of panels, (ii) pump max. head & flow?	

29.	What make (brand) of a system do you have? And did it come with any warranty or service conditions? If yes, provide detail.	
30.	Does your system use batteries/water tanks or both? If yes, specify capacities and indicate the benefits you are deriving from these accessories?	
31.	What is the size of your irrigated land? And what crops do you grow under solar powered irrigation?	
32.	Where do you "vision" the solar pump sector in 10 to 20-years in terms its level of adoption, and role in advancing the SDGs?	
33.	Can data or other information be shared on number of installations or other relevant indicators in specific geographies	