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Feasibility of Solar-Powered Groundwater Pumping Systems in Rural Areas of Greater Giyani Municipality (Limpopo, South Africa)

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Abstract: Rural areas in Limpopo Province (South Africa) are in urgent need of interventions for safe and secure water supply to adapt to climatic changes and the increased frequency of droughts. A feasibility study was conducted for the adoption of solar-powered groundwater pumping systems and Multiple Water Use Services (MUS) in Greater Giyani Municipality (Limpopo). Stakeholder engagement, geotechnical data and socio-economic information were used in the feasibility study. The Solar Powered Irrigation Systems (SPIS) tool (GIZ and FAO, 2021) was used to design solar-powered shallow groundwater pumping systems at nine case study sites: four villages (water supply for domestic use) and five small-scale farms. Given the technical design configurations, peak water requirements ranged from 28.8 to 58.9 m^3/d, peak power requirements from 1.2 to 3.4 kWp and required solar panel surface areas from 8.0 to 22.3 m^2. Viable financial mechanisms for the operation and maintenance of MUS are leasing, cooperatives, informal saving groups and pay-per-use. The adoption of the technology appears to be financially and technically viable to augment the water supply. However, groundwater levels will have to be monitored and water purification plants for drinking water will have to be established to ensure long-term sustainability.

Keywords: climate change adaptation; community engagement; multiple water use services (MUS); rural water supply; shallow aquifers; solar-powered irrigation systems (SPIS)

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Citation: Jovanović, N.; Mpambo, M.; Willoughby, A.; Maswanganye, E.; Mazvimavi, D.; Petja, B.; Molose, V.; Sifundza, Z.; Phasha, K.; Ngoveni, B.; et al. Feasibility of Solar-Powered Groundwater Pumping Systems in Rural Areas of Greater Giyani Municipality (Limpopo, South Africa). *Appl. Sci.* **2023**, *13*, 3859. https://doi.org/10.3390/app13063859

Academic Editor: Georgios Papadakis

Received: 10 February 2023
Revised: 4 March 2023
Accepted: 16 March 2023
Published: 17 March 2023

1. Introduction

South Africa is extremely vulnerable and exposed to the impacts of climate change [1] within both its socio-economic and environmental settings. Increased occurrence of extreme climatic events comes with negative implications for infrastructure, health, production and economic growth. These impacts will increase water supply pressure in already water-stressed environments [2]. The marginalized and poor are particularly affected by the impacts of climate change [3]. An indirect benefit of improved and secure water supply is that health risks of dependent communities are minimized. This is particularly important in the context of pandemics as people with the least access to essential services such as water will feel the most dramatic effects. Large portions of the rural population in South Africa lack access to basic hand-washing facilities in their homes or they experience partial access and regular shut-offs. Investing in long-term water security and access to clean water and sanitation is therefore a matter of public health. This advocates for a balanced planning and response to climate change while adapting to the new normal.

In the South African context, where water resources are fully allocated in most catchments, shallow groundwater and alluvial aquifers of ephemeral (or dry sand bed) rivers are potential alternative sources of water. Groundwater is notoriously under-utilized, although it is heavily relied upon especially in rural areas [4]. Water resources contained within alluvial aquifers have been utilized for centuries by local communities, in particular in resource-poor rural areas through low-tech and unregulated means [5,6]. Previous research on an ephemeral river in the Limpopo Province of South Africa (Molototsi River) indicated that sustainable utilization of these groundwater resources is possible, provided this is carried out in a controlled and monitored manner [7]. Given the fact that the majority of the poor and water/food-insecure households in South Africa are still concentrated in rural areas, there is an opportunity to improve water availability, and shallow groundwater and ephemeral rivers have the potential to be alternative water sources for multiple uses (domestic, agricultural crop and livestock production). This warranted the investigation of possible interventions to improve water security in light of the changing climate.

One of the potential interventions refers to a recently developed approach for water supply and provision of water services in rural areas, namely Multiple-Use Water Services (MUS) [8]. The multiple-use water scheme is a community-based water services provision system built on the principles of decentralization, community participation and empowerment, with the objective of improving the provision of water services and the impacts on livelihoods. Examples of real-life MUS applications in several countries were presented by [8–10]. These examples of participatory MUS in remote rural areas were meant to provide water for a multitude of users, namely drinking water supply, water for sanitation and hygiene, conventional and unconventional irrigation, micro-hydropower, water mills and livestock watering. Community participation is required to define the sharing of costs and benefits, manage competing demands, prevent over-use of water sources and achieve necessary institutional reforms in the inception, design and planning stages. The main conclusions from these studies were that the participatory MUS approach improved the access, availability, quality and reliability of water services in households; however, an enabling environment is required at the level of local governance to promote inter-sectorial collaboration and community participation.

Many rural communities in South Africa are not supplied with grid electricity. Renewable energy is a logical route that could be adopted in order to secure sufficient and reliable energy for water supply in remote areas while increasing the resilience to a changing climate. The use of photovoltaic solar cells for pumping water has been steadily increasing in the last decade, particularly in developing countries such as China and India, but also in many European and African countries [11–13]. Hartung and Pluschke [14] reported that there is a growing interest in solar-powered irrigation and conducted a review of historic and current trends that included surveys, interviews and site visits covering many case studies worldwide. GIZ [15] summarized some fundamental opportunities for the use of solar-powered groundwater pumping systems (e.g., low operational costs, low environmental impacts, growth of photovoltaic cell markets, remedying unreliable grid power and connection to the grid) as well as some hurdles (e.g., high initial capital investment, the lack of financing and policies, exposure of equipment to weather extremes and theft). Ref. [16] highlighted that the adoption of solar energy for irrigation is an attractive option, however a technical and economic assessment is required to determine feasibility at specific sites. The results from five case study sites (in Spain, Saudi Arabia, USA, Lebanon and Jordan) indicated that solar-powered irrigation is technically feasible and sustainable in areas with high solar radiation as long as groundwater has sufficient capacity to recover and enough land is available for solar arrays. The economic benefits outweigh the conventional fossil fuel and electricity systems in the long run, although the initial capital costs are high.

Feasibility assessments were conducted in previous international research for solar-powered groundwater pumping systems [15,17]. A reliable water source of acceptable quality is the main pre-requisite for the success of the interventions. Equally to water, the availability of solar radiation and land, groundwater depth and aquifer hydraulic characteristics, water storage infrastructure and required hydraulic lift, required volumes and operating flow rates, suitable topographic and climatic conditions, land use/cover, earthworks required and distance to roads are essential geotechnical aspects to be considered [18–21]. For the technical and engineering feasibility, a number of procedures and tools were published for the design, configuration and sizing of solar cells, controllers and groundwater pumps [22–25]. A number of applications and optimization studies for solar-powered pumping systems were reviewed in [26]. Modi [27] provided a number of practical recommendations for small-holder farmers in a developing country based on a case study conducted in Senegal, including benefits from bulk procurement, logistics, transaction costs and interconnectivity to the grid. Dedicated software was also developed [28,29] as well as procedures for performance analysis and optimization [30–32]. The technical assessment also includes the manufacturing of the system, its efficiency, longevity and utilization [12,33], data requirements and monitoring [14,15].

The socio-economic feasibility of the systems was investigated in the literature through users' perception [15,34]. Agrawal and Jain [11] proposed 14 determinants for the sustainability of solar-powered irrigation systems that relate to the social, economic and environmental sustainability. Ref. [11] also proposed strategies to promote the adoption and expansion of the technology, including building awareness, prioritizing areas for deployment, business models, subsidies and policy support. A business model for the management and maintenance of solar-powered groundwater abstraction systems and MUS needs to be put in place [15], ideally run by communities and gender-unbiased, for which policy support, financing and capacity development are often required [13,14,35–37]. The choice of the appropriate business model for MUS depends ultimately on the community and the social set-up.

Amongst all costs, the cost of energy is one of the most recurrent and highest in intensive irrigated agricultural systems [38], especially for small-holder farmers that are using diesel and electricity pumps for irrigation. Photovoltaic solar generators could represent a potential alternative source of energy to reduce the cost of electricity consumption as the price of this technology is declining [15]. A number of studies used economic analyses to demonstrate the financial viability of solar-powered groundwater pumping based on capital investment costs, operational costs and payback periods [14,17,28,39,40]. The major outcome of these studies was that solar energy is more financially viable than diesel. Hybrid systems with solar energy and connection to the grid for electricity supply during periods of non-operation are also possible, as discussed by [14,41].

From the environmental and sustainability perspective, energy supply is a focal point. It was estimated that about 7% of the total world energy consumption is used for water supply [42]. Reductions in CO_2 emissions with the use of solar pumps were previously quantified compared to other sources of energy by [14,25,40]. Solar pumps may also enhance carbon sequestration by increasing biomass production through irrigation of grasslands and crops [12]. However, one of the major risks is that the low operational cost of solar-powered groundwater pumping may result in an over-abstraction of groundwater and water resource quality deterioration [14,19,43,44]. Life cycle assessments of solar-powered groundwater abstraction were conducted in previous work to examine the impacts of the technology from cradle to grave, including the handling of e-waste [45,46]. The general conclusion from previous feasibility studies was that solar energy is more environmentally and economically viable than diesel and electricity [47,48]. Despite the obvious advantages of renewable energy sources in terms of profitability and reduced environmental footprint, the use of energy sources based on fossil fuels (oil, coal, gas) outweighs by far solar energy [49]. Although the solar pumps technology is mature, the adoption is not widespread due to the high initial capital investment and the specialized skills required in the design, installation and maintenance.

A comprehensive feasibility study on the utilization of local-scale alternative water source interventions and associated technologies for water abstraction and supply has not been carried out in South Africa. This study aimed at investigating the technical, socio-economic and environmental feasibility for the establishment of MUS and solar-powered groundwater pumps in rural communities of Greater Giyani Municipality (Limpopo) in order to provide a secure water source for domestic and agricultural purposes from non-perennial river sand banks and shallow aquifers. Given the site-specific characteristics of the application, it was not possible to consider a large area (e.g., province or district). Greater Giyani Municipality was considered because it is a critical area in terms of water scarcity and drought occurrence. The envisaged outcome was to improve the resilience of rural areas to a changing climate, which is characterized by recurring climate extremes, and also to encourage sustenance of rural livelihoods. The paper is structured into the following sections: (i) the Materials and Methods describe the study site and the methods used, namely the community engagement process, the toolbox on "Solar Powered Irrigation Systems (SPIS)" [50] and water quality fitness tests; (ii) the Results summarize the outcomes of stakeholder workshops, the socio-economic assessment and technical design at nine pilot sites with SPIS [50] and the source water quality; (iii) a comprehensive discussion is then provided on the site-specific characteristics, benefits and constraints, as well as the operational and monitoring requirements; (iv) the Conclusions outline the implications of the findings for implementation and long-term sustainability.

2. Materials and Methods

2.1. Description of Study Area

The study area is located in Greater Giyani Municipality (Mopani District) in the Limpopo Province (Figure 1). Greater Giyani is a rural municipality which has a single semi-urban area, Giyani town, with a population of 256,300 exhibiting a slight tendency to decline mainly due to migration to cities [51]. A large number of rural settlements are scattered and not easily accessible as the road conditions are bad and this has implications for economic activities in the municipality. The climate is summer rainfall sub-tropical, with an average annual temperature ranging from 18 °C to 28 °C. The area receives between 200 and 450 mm a^{-1} of rainfall, predominantly during summer (from October to March), strongly influenced by topography along the west–east gradient.

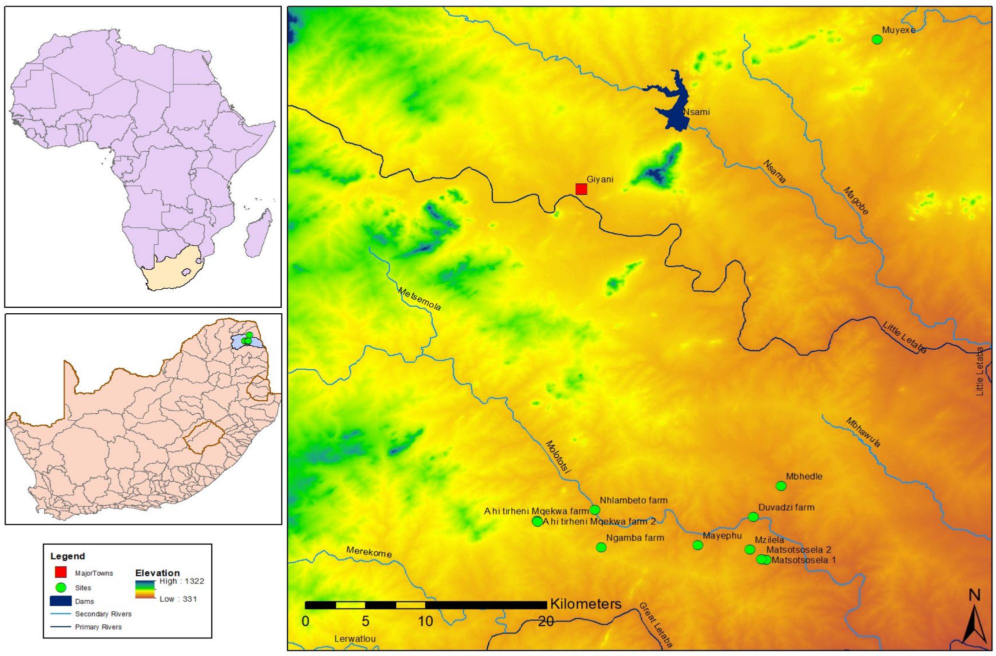

Figure 1. Topography map of the study area and location of 9 case study sites.

The study area is located between the perennial Great Letaba River and the non-perennial Molototsi River that flows occasionally a few times per year. The village of Muyexe is located in the Shingwedzi catchment (Figure 1). The land use/cover is predominantly thicket/dense bush (mopani trees), woodland/open bush, grassland, cultivated subsistence land and urban settlements (villages). The main economic activities are agriculture (citrus, mango and tomatoes), tomato processing (secondary sector) and eco-tourism (tertiary sector) [52]. A large part of the catchment consists of arable land with subsistence farming dominating over commercial farming.

The geomorphic features of the study area include low mountains of the Great Escarpment (to the west), undulating and irregular plains, hills and lowlands (Lowveld towards the east). The area is at the interface between the granitic-greenstone of the KaapVaal Craton and the metamorphic (predominantly gneiss rocks, but also schist) of the Southern Marginal zone of the Limpopo Mobile Belt [53]. Groundwater is typically retained in fractured rock aquifers (regional groundwater) and alluvial aquifers along river courses. The estimated groundwater use is 30–40% of groundwater recharge [52]. Borehole yields are moderate to high, typically around 2 $L \cdot s^{-1}$. Limited groundwater development may be feasible in the Molototsi catchment, given groundwater is abstracted below harvest potential, groundwater yields and quality are reasonable and groundwater contributes little to baseflow [52].

The largest user of the available water resources is irrigation, while other significant users include forestry and rural domestic. Mopani District is the water service authority through an agreement for water service provision with the Department of Water and Sanitation. Water sources within the Mopani District are streams, wells and boreholes, with most water supply depending on dam capacity. Besides dams, infrastructure includes reservoirs, reticulation networks, especially in urban areas, street-taps and borehole pumps. However, the current water supply infrastructure in Greater Giyani Municipality is inadequate because villages are sparse, which makes it difficult and expensive to provide a reticulation system [54], coupled with the increased demand for water in villages, where 42.83% of the households do not have access to water supply and 33.8% do not have access to electricity. Sanitation is also a major problem, which also contributes to health hazards and groundwater pollution. Pit latrines are used by 45.5% of the population and 74.9% have no sanitation facilities at all [51]. A service level agreement between the district and local municipalities results in a complex relationship for the provision of water. The two entities together provide free basic water to households with subsidies for the diesel and electricity for pumping water to the communities.

The population is relatively evenly distributed throughout the study area, living both in urban areas (Giyani and Tzaneen) and in informal rural villages and settlements. The agriculture sector employs 8.37% of the workforce [55]. The main sectors contributing to the Gross Domestic Product in Greater Giyani Municipality are the public sector (public administration and local government services), tourism, agriculture, retail (formal and informal) and transport [56]. Agriculture is an important activity thanks to favorable climate, variety of products and potential in processing agricultural products. Most of the rainfed cultivation and cattle herding are practised as subsistence farming on communal lands. Irrigated agriculture makes a significant contribution to the economy and is a major user of water. Farmers who practice irrigation in the study area market their crops through both formal and informal markets (hawkers, local markets, supermarkets and national fresh produce markets). Agricultural land in Greater Giyani Municipality is predominantly government land and it is administered by traditional authorities, under the Permission to Occupy system of land tenure.

2.2. Stakeholder Engagement

An initial list of 46 villages was drafted in order to undertake a process of stakeholder engagement. These were then clustered into 6 groups and half-day stakeholder workshops were conducted. Participants for the workshops were selected amongst community members to represent both the political sphere and traditional authorities, and individuals that will be directly involved in the operation and maintenance of the systems: water and farmers' committee members in villages, pump operators, municipal water managers, ward councilors, prominent citizens and volunteers. During the workshops, the research team firstly presented the project to raise public awareness and promote the interventions amongst key community members. The initial design and installation of the equipment and infrastructure was then explained to the community along with the modes of investment and financing, the requirements for long-term sustainability, operation and maintenance, including safety and security issues, with the main intent to secure a sense of ownership by the community. This was followed by exchange of information and discussion on the way forward followed by physical visits to sites where the community proposed interventions to take place.

A number of criteria were considered to determine potential case study sites for the feasibility investigation. These criteria were (i) availability and reliability of a water source (groundwater borehole or shallow wells in sand river banks); (ii) community needs (water demand); (iii) crop water requirements for small farming; (iv) water use diversification opportunity; (v) current infrastructure gaps; (vi) system set-up and logistical complexity; (vii) economic activity potential (e.g., agriculture and possibility of value-added products); (viii) access to markets and geographic access; (ix) tribal and traditional support; (x) health and hygiene improvements; (xi) cultural activity and economic potential. A list of nine case study sites was therefore compiled for the feasibility study on solar-powered groundwater pumping systems and MUS, namely four villages in dire need of water supply for domestic use and five small-scale farms: (i) Mbhedle, (ii) Mayephu, (iii) Mzilela and (iv) Matsotsosela villages, (v) Nhlambeto Primary Agricultural Cooperative in Dzumeri village (mixed domestic and small-holder irrigation water use), (vi) Matsambo Ngamba Projects, (vii) A hi tirheni Mqekwa Primary Agricultural Cooperative, (viii) Duvadzi Youth Organic Agricultural Cooperative and (ix) Macena Primary Agricultural Cooperative. The locations are indicated in Figure 1 and their characteristics are summarized in Table 1.

2.3. Feasibility Study

The core methodology used in the feasibility investigation was the toolbox on "Solar Powered Irrigation Systems (SPIS)" [50]. The SPIS toolbox was developed primarily for small-scale irrigation. Where necessary and possible, the toolbox was adapted and populated with data to fit the multi-purposes of MUS schemes. The toolbox consists of a handbook structured in modules and a number of tools in Excel and Word. The following modules were used in this study: Impact Assessment Tool, Water Requirements, Market Assessment Tool, Farm Analysis Tool, Payback Tool, Finance Deployment Tool and Pump Sizing Tool.

The Impact Assessment Tool consists of a questionnaire where scores and weights are assigned to environmental and socio-economic impacts. The questionnaire was compiled with information based on long-term research and experience gained in the study area, as well as based on feedback from stakeholder engagements during field visits.

The Water Requirements spreadsheet is used to calculate crop or livestock water requirements. It is therefore one of the key tools for the design of solar-powered pumping systems. The tool is a spreadsheet that makes use of the FAO methodology [57] based on the FAO 56 Bulletin to calculate crop water requirements [58,59]. For the purpose of estimating agricultural water requirements, a hypothetical cropping pattern was chosen with three tomato crops grown on 0.5 ha and planted on 1 December, 1 May and 1 October of the year. Tomato is a popular vegetable in the area and its water consumption is generally higher than other common vegetables (worst-case scenario of crop water requirements). Crop growing period was from 135 to 158 days according to FAO 56 guidelines [58]. Drip irrigation with 90% efficiency was selected as well as normal spacing of plants. Weather data from 2012 to 2020 collected with a weather station in Giyani (Agricultural Research Council; Lat: −23.32403; Long: 30.68730; Alt: 463 m) were used as inputs. Monthly average temperatures were entered in the spreadsheet to calculate reference evapotranspiration ETo and average monthly rainfall was added to calculate effective rainfall [58]. In addition, livestock water requirements were calculated based on the recommendations of [60]. For livestock water requirements, it was hypothesized that the farms (Table 1) breed 5 adult dry cattle. For the study sites supplying water for domestic use (Table 1), water requirements were estimated by multiplying the population of the village by the minimum average basic consumption of 25 L per person per day, according to South African norms.

The Market Assessment Tool defines the business conditions and their relevance. Appropriate parameters were chosen from drop-down lists and by making use of links to web sites provided within the tool to extract general information from global reports and databases. The relevance was selected based on given categories (inconsequential, slightly important, important, very important and critical). The input weightings were kept as default.

The Farm Analysis Tool is used to perform a financial analysis of a farming enterprise to assess agricultural productivity and profitability. It consists of spreadsheets to calculate fixed and variable costs and farm profit/loss. Information on realistic income and expenses was collected directly from small-holder farmers and agricultural extension officers during the stakeholder engagement. This was used to calculate a typical profit margin for a small-holder farm.

The Payback Tool is used to compare the financial feasibility of three different pumping options: solar-powered, grid-powered and diesel-powered. Input data were populated with realistic capital and maintenance costs of these systems. The life spans of the system components were estimated according to general knowledge and based on specifications of manufacturers. The Payback Tool summarizes the results of the financial feasibility in tabular and graphical format for Internal Rate of Return (IRR) and Net Present Value (NPV) over 25 years, accumulated cash flow after 25 years, system life cycle costs for 25 years, years of payback, yearly loan repayment (if applicable) and yearly CO_2 emissions of the three systems.

The Finance Deployment Tool is a spreadsheet questionnaire used to identify possible financial mechanisms (products and services) that could be used for the operation and maintenance of MUS. Depending on the Yes/No answer to the questionnaire, the tool excludes/retains potential financial products and services. The questionnaire was compiled based on information obtained during the stakeholder engagement and knowledge of the area.

The Pump Sizing Tool was used to configure and design solar-powered groundwater pumping systems for the nine case study sites, namely the required hydraulic lift, power and pump type, the required peak power and the solar panel surface area. Required hydraulic head was calculated based on measurements of groundwater depth and the required hydraulic lift to storage reservoirs.

Water quality fitness for a specific use is a pre-requisite for the success of the MUS system. Groundwater samples were therefore collected from water sources at all case study sites and analyzed in the laboratory for chemical and physical properties according to standard procedures (in May 2022 at the end of the rainy season and November 2022 at the end of the dry season). Water quality fitness for irrigation on small-holder farms was assessed by comparison with the South African Water Quality Guidelines for agricultural use [61]. Water quality fitness for drinking purposes was evaluated by comparison with the South African National Standard for drinking water SANS 241: 2015. The water quality evaluation also served to identify the need for water purification or filtering systems.

Table 1. Case study sites, their water use, water requirements, total dynamic head, pipeline length and diameter, power supply required (peak kW) and solar panel surface area estimated for each proposed pilot site with the Pump Sizing Tool [50].

Village	Site	Water Use	Borehole Depth (m)	Water Requirements (m^3/d)	Total Dynamic Head (m)	Pipeline Length (m)	Pipeline Diameter (mm)	Peak Power (kWp)	Solar Panel Surface (m^2)
Mbhedle	Population = 1230	Domestic, livestock	80–90	30.8 [1]	33	1000	60	1.5–1.7	10.0–11.3
Mayephu	Population = 1940	Domestic, livestock	80–90	48.5 [1]	30	50	60	2.2–2.7	14.3–18.0
Mzilela	Population = 1150	Domestic, livestock	80–90	28.8 [1]	29	50	60	1.2–1.3	8.0–8.7
Matsotsosela	Population = 2300	Domestic, livestock	80–90	57.5 [1]	30	50	60	2.8–3.4	18.7–22.3
Dzumeri	Nhlambeto Primary Agricultural Cooperative	Domestic, agriculture	4	58.9 [2]	20	300	60	1.7–2.0	11.0–13.0
Dzumeri	Matsambo Ngamba Projects	Agriculture	66	33.9	35	150	40	1.7–2.0	11.3–13.3
Dzumeri (Daniel Ravalela)	A hi tirheni Mqekwa Primary Agricultural Cooperative	Agriculture	120	33.9	43	300	40	2.1–2.6	14.0–17.3
Loloka	Duvadzi Youth Organic Agricultural Cooperative	Agriculture	120	33.9	35	150	40	1.7–2.0	11.3–13.3
Muyexe	Macena Primary Agricultural Cooperative	Agriculture	40	33.9	40	250	40	2.0–2.5	13.0–16.7

[1] Calculated as population × 25 L/person/d. [2] Calculated as farm water requirement + requirement of 1000 people (fraction of population of Dzumeri).

3. Results

3.1. Outcomes of Stakeholder Engagement

Stakeholder workshops were organized for clusters of villages to identify/assess the conditions in terms of the water challenges that exist, the state of the water infrastructure, water uses and most importantly to educate the community about solar water pumps and their benefits. The field visits were also about engaging the community members on their willingness to accept and support the use of solar panels as an alternative power source for their water abstraction. Given the water scarcity in the area and the lack of regular water supply in the villages, the main outcome of the workshops was that the communities are in urgent need and very supportive of the proposed interventions. This was evidenced through the attendance to the workshops, the participation in the discussion and explicit expressions of support. The communities were also willing to be trained in the operation and maintenance of the systems. Concerns were, however, expressed about the potential risks of theft and vandalism.

Most of the challenges put forward during the community workshops revolved around the following problems on the ground: (i) lack of water supply system due to lack of infrastructure or break-ups and damages to infrastructure; (ii) lack of secure water supply (in some instances, villages are connected to bulk water infrastructure, but water supply is not regular, in most cases occasional, once a week to once a month); and (iii) distance to be covered by villagers to collect water on a daily basis. Given the urgent need for reliable water supply intervention, the case study sites were considered based on the existence of infrastructure (e.g., existing boreholes, reservoirs, etc.) and specific community needs. Some sites were not considered because they already had an operating water supply system in the vicinity (although frequently intermittent), because they needed major infrastructure work such as laying down pipes, reticulation systems or drilling boreholes, because parts of the system needed repair/replacement, they were stolen or vandalized, such as pumps, cables, reservoirs, or because the distance from the water source is too far for the establishment of a manageable solar field. As a result, the choice of the case studies was narrowed to nine sites (Table 1).

3.2. Feasibility Assessment

A socio-economic and environmental impact assessment for the study area was conducted with the Impact Assessment Tool of SPIS [50]. Figure 2 represents the SPIS output graph with the results obtained. Categories on population change and migration, women's role, and minority and indigenous groups were not specifically investigated (Figure 2). However, the introduction of solar-powered groundwater pumping schemes operated as MUS will undoubtably improve employment and economic opportunities, which may contribute to a decrease in population migration from the study area, and improvements in the social status of women through the provision of water supply and service, market opportunities, integration and equitable access to resources and institutions and time relief for other activities such as education, leisure and training. Similarly, the reliable water supply will impact positively on the lifestyle and livelihoods of minority and indigenous groups. A major positive impact of the intervention is expected in terms of income and amenities (Figure 2) through economic changes, improvements of livelihoods and well-being, equitable distribution of income and business opportunities with spin-offs in terms of diversification of production, technical services and markets, creation of agricultural services, employment opportunities and building of infrastructure. The intervention is not expected to substantially impact political changes, social harmony or regional effects in the country due to its localized nature (Figure 2). However, although the improvement of food supply is targeted to local communities, there is a realistic chance that produce will be marketed outside the study area, in markets in Limpopo and other provinces. The intervention can also contribute to strengthening the agricultural products value chain (transport, marketing and processing). The category of user involvement scored high in the impact assessment (Figure 2) through the engagement of stakeholders, public participation, discussions with the community on credit and marketing opportunities, their needs and preferences, as well as the training of communities in the use of the solar-powered water supply systems. Concerning the impacts on natural resources and the environment (Figure 2), the intervention will certainly modify the water balance (evapotranspiration, groundwater storage, baseflow) through increased groundwater abstraction. Sustainable water abstraction limits can be set for each specific site (borehole, well), for example by switching off the pump automatically when a certain groundwater level has been reached. Groundwater quality as a result of irrigation return flow is not deemed to be a problem, mainly because small-holder farms are spaced apart. Salinization and other impacts on the soil (acidification, alkalinisation, waterlogging) are not expected in the short-term, however this should be monitored in the long-term. Land degradation through soil erosion represents a big problem in the area and it manifests through sheet, gulley erosion and soil compaction below the ploughing layer. The increased use of fertilizers and pesticides will have to be monitored.

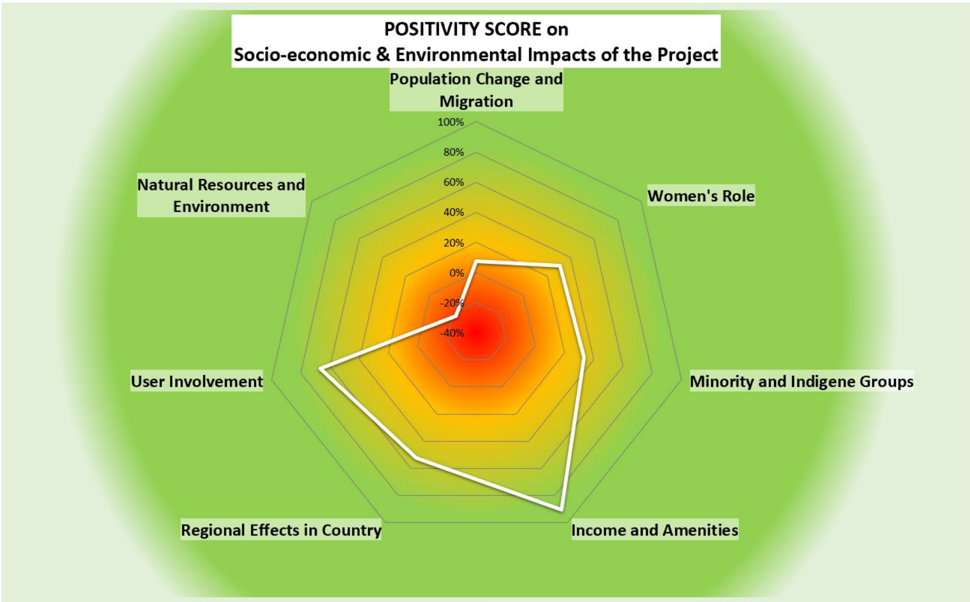

Figure 2. Screen printout of the impacts of solar-powered groundwater pumping operated with MUS for the study area, generated with SPIS [50]. High scores indicate positive impacts, low scores indicate negative impacts.

Water requirements for the case study farms (Table 1) were calculated with the Water Requirements Tool of SPIS. The output results are shown in Table 2. Monthly crop water requirements vary depending on the season, the atmospheric evaporative demand, effective rainfall and overlapping crop growing seasons (planting dates). The highest values were recorded in the summer months (December to March) and the lowest in winter (April to July). The maximum crop water requirement of 33.4 m^3/d was calculated in December whilst the minimum was in May (10.4 m^3/d) (Table 2). Livestock water requirement was negligible compared to irrigation water requirement. The seasonal patterns of total water requirement for the farm were therefore similar to crop water requirement with a peak in December (33.9 m^3/d). A volume of 33.9 m^3/d would equate to the water supply to a village of about 1350 people at a rate of 25 L per person per day. Total annual water requirement for the farm was calculated to be 8386 m^3/a. Pump utilization rate was calculated to be 68% depending on the monthly fluctuations in water requirement, as the pump has to satisfy the water demand in the peak month, and it is under-utilized in the remaining months of the year. Different scenarios of crops, cropping patterns and planting dates can be built to optimize water requirements and pump utilization. The combinations are infinite; however, this will depend on the farmer's choice and other farming activities.

Table 2. Farm water requirements generated with the Water Requirements Tool of SPIS [50] showing daily water requirements for crop production, livestock and total for each month of the year.

Crop Water Requirement (m^3 d^{-1})													
Crops	**Area (ha)**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Tomato	0.5	10.1	22.1	29.9	12.1	-	-	-	-	-	-	-	7.2
Tomato	0.5	-	-	-	-	10.4	15.3	19.8	27.8	24.8	6.9	-	-
Tomato	0.5	19.8	4.8	-	-	-	-	-	-	-	13.4	20.6	26.2
Total	1.5	29.9	26.9	29.9	12.1	10.4	15.3	19.8	27.8	24.8	20.3	20.6	33.4
Livestock water requirements (m^3 d^{-1})													
Livestock	No. of heads												
Cattle (adult, dry)	5	0.5	0.5	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.5	0.5
Total water requirements (m^3 d^{-1})													
Total		30.4	27.4	30.4	12.3	10.7	15.5	20.0	28.0	25.0	20.8	21.1	33.9

The results of the Market Assessment Tool [50] indicated a total score of 53.23% for market potential of SPIS in Greater Giyani Municipality with a number of factors being inconsequential and others being rated as important. The site has high market potential in terms of climatic and geophysical settings. Government interventions result in moderate market potential mainly due to the lack of policies and laws promoting solar energy. The involvement of development organizations results in high market potential. Financing by end users and institutions as well as the availability of alternative power sources, subsidies and costs result in moderate market potential. A low market potential score was obtained for technical capacity, mainly because of a lack of training programs and university curricula on solar technologies. However, awareness and adoption of solar technologies are increasing, and the presence of suppliers results in a high market potential. The significance of agriculture in the local economy is comparatively low compared to other sectors (e.g., mining and industry) resulting in marginal market potential. The relevance of land tenure is important, whilst the transportation and communication infrastructure are good but deemed to be inconsequential, both resulting in moderate market potential.

The Farm Analysis Tool of SPIS [50] was used to perform a financial analysis for the design of solar-powered groundwater pumping systems for the farming case studies (Table 1). In this example, the calculation was performed for a hypothetical small-holder farm but based on realistic income and cost inputs. The emerging farmer has 5 ha of land under Permission to Occupy tenure; 2 ha are under rainfed seasonal crops (e.g., maize), 0.5 ha is under irrigation (three seasons of vegetable crops) and 2.5 ha are under fallow land in rotation. The farmer has 5 heads of cattle. Given these settings, it was calculated that the annual gross farm income is ZAR 334,500, the total annual costs are ZAR 82,900, resulting in an annual gross farm profit of ZAR 251,600. This value was retained for the calculation of the payback period of solar-powered groundwater pumping systems (Figure 3). In the real world, each case study farm may have different cropping patterns and the income and costs depend on the specific year, weather conditions and market prices.

The Payback Tool of SPIS [50] was used to compare the financial feasibility of three different pumping options: solar-powered, grid-powered and diesel-powered. The gross farm profit was ZAR 251,600 a^{-1} (calculated in the Farm Analysis Tool) and the proportion of profit to invest in paying off the pumping system was assumed to be 20% with an estimated inflation rate of 6%. The initial capital and running costs for the three options were estimated based on current market prices. For the grid-powered system, the pump power demand was estimated to be 2 kW, the required pump flow was 4.2 m^3/h for 8 h of work per day (peak water demand was calculated to be 33.9 m^3/d) with 180 d of irrigation per year. The cost of electricity was assumed to be 3 ZAR/kWh. For the diesel-powered pumping system, the additional inputs were the fuel demand of the power generator, estimated to be 1 L/h, and the cost of fuel, assumed to be 18 ZAR/L.

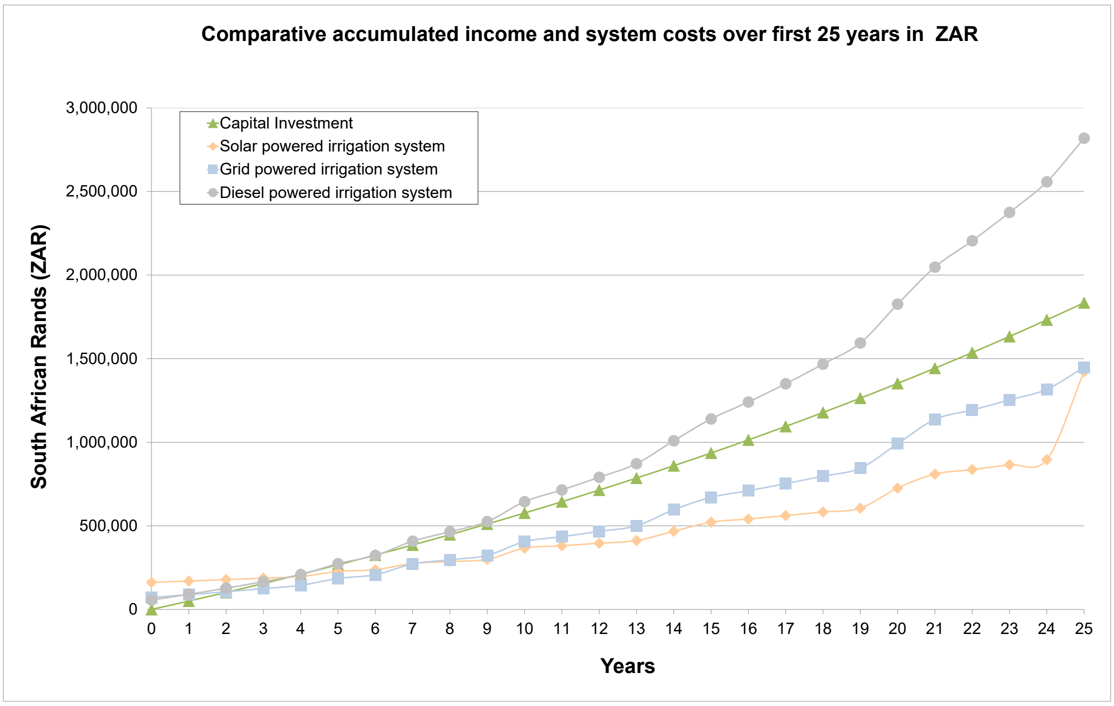

Figure 3. Accumulated income and system costs for groundwater pumping using solar panels, grid electricity and diesel over 25 years generated with the Payback Tool of SPIS [50].

The financial feasibility performed with the Payback Tool indicated that the grid-powered system has the highest IRR, whereas the solar-powered system has the highest NPV and accumulated cash flow over 25 years (Table 3). The life cycle cost is the lowest for the solar-powered system, which will take 4 years to pay back compared to 3 years for the grid-powered system. With the current input data, the diesel-powered pumping system is not financially viable (Table 3). For diesel-powered pumping to be viable, the gross profit of the farm should be at least ZAR 390,000 per year. Likewise, if a proportion of the profit for payback is <20%, none of the systems would be feasible. Emissions of CO_2 will occur from the grid-powered system and especially from the diesel-powered system (Table 3).

Table 3. Financial feasibility of three different groundwater pumping options calculated with the Payback Tool of SPIS [50].

Financial Indicator	Solar-Powered	Grid Electricity	Diesel
Internal rate of return over 25 years	25%	43%	Not feasible
Net present value over 25 years (ZAR)	4,063,542	2,962,363	−2,870,302
Accumulated cash flow after 25 years (ZAR)	412,398	385,915	−984,141
System life cycle cost (25 years) (ZAR)	1,422,232	1,448715	2,818,771
Years to payback	4	3	No payback
CO_2 emissions per year (kg·a^{-1})	0	956	3869

The cumulative income and system costs over 25 years are shown in the graph in Figure 3. The solar-powered system has the highest capital investment cost that is reflected in the first few years on the graph. The solar-powered capital investment is paid back after 4 years and, starting from year 7, the cumulative costs become lower than for the grid-powered system. From then on, the solar-powered system has the lowest cost throughout the lifespan of 25 years, amounting at >ZAR 400,000 lower cost than the grid-powered system at year 24. Fluctuations of the curves depend on the replacement value and life span of the various components. The cumulative costs of solar-powered systems increase sharply after 25 years, which is the time span of solar panels when these will have to be replaced. The cost of diesel-powered systems is by far the highest over-shooting the adjusted capital investment value from year 9 (Figure 3). Many other examples of calculation can be constructed. If the irrigated area is increased or more population needs to be supplied with water, this would imply increased water requirements, more solar panels needed, a more powerful pump (kW) to satisfy the delivery of required flows as well as more kWh consumed. This scenario could be financially more viable because the gross farm profit would increase; on the other hand, it would increase the risk of groundwater over-abstraction and jeopardize the geophysical feasibility.

The Finance Deployment Tool was used to identify possible financial mechanisms for the operation and maintenance of solar-powered groundwater pumping systems. For the specific study sites, the users are not expected to have collateral assets, soft collateral or other guarantees for loans, alternative sources of income, established value chains or cooperative programs, and they do not possess initial capital. However, the users have bank accounts, mobile devices, they are able to pay commercial interest rates and they live in communities with common goals and reciprocal trust. They may be willing to use solar-powered pumps without buying them, pay monthly fees into a common trust and depend on other users according to an agreed schedule. Specifically, agricultural water users require a regular supply of water for irrigation and livestock, they are subsidized by government and there is interest from the private sector to purchase their products. After exclusion of unfeasible financial mechanisms, the following options are available: leasing, cooperatives, informal saving groups and pay-per-use. These are feasible financial mechanisms for the operation and maintenance of solar-powered groundwater pumping schemes through MUS.

Based on the information collected above, the design and sizing of solar-powered groundwater pumping schemes were carried out for each individual case study site (Table 1) with the Pump Sizing Tool of SPIS [50]. It was assumed that an average of 6 sun hours per day occur at an average solar irradiation of 4.9 kWh/m^2/d calculated from the weather data measurements at Giyani weather station. A default solar system power loss of 25% was assumed with a fixed (non-tracking) solar panel array. Borehole yields in the fractured rock system are very variable; however, a realistic figure for borehole yields is 2 L/s as reported in previous studies [53,62]. The estimated water source yield was therefore 173 m^3/d (2 L/s) with 50% sustainable extraction rates. Required daily water pumping rates corresponded to peak monthly water requirements calculated for each farm and village. Farms usually use 40 mm (1.5 inch) conveyance pipes and communities 60 mm (2.4 inch) pipes for drinking water, with a variable pipe length and fittings determined for each specific site. Table 1 summarizes water requirements, required total dynamic head, pipeline length and diameter for each study site.

The Pump Sizing Tool calculated the peak power requirement (kWp) and the required solar panel surface. Required valves and fittings were also entered in the program to calculate pressure losses based on realistic piping system configurations. Each study site has different characteristics in terms of water requirements and pressure heads to be delivered by the pump depending on the geophysical settings. Water requirements depend largely on the size of the population to be supplied with water, ranging from 28.8 m^3/d for Mzilela to 58.9 m^3/d for Nhlambeto farm in Dzumeri (mixed water use). Water requirements on farms, assuming the same cropping system and irrigation area as the hypothetical farm, are the same (33.9 m^3/d) because the same climatic data were used. Nhlambeto farm is the only site using shallow groundwater from the riverbed alluvium, so it has the lowest total dynamic head requirement of 20 m. A hi tirheni Mqekwa farm pumps water from boreholes that are quite distant from the irrigated field, and it requires the highest total dynamic head of 43 m. The village of Mbhedle requires the longest conveyance pipe (1000 m), but the water requirement is quite low, so the estimated total dynamic head is 33 m. The peak power requirements ranged from 1.2–1.3 kWp at Mzilela, with the lowest population size, to 2.8–3.4 kWp at Matsotsosela with the highest population. This corresponds to a solar panel surface area requirement of 8.0–8.7 m^2 at Mzilela and 18.7–22.3 m^2 at Matsotsosela. Fairly high peak power requirements and large solar panel areas were calculated for Mayephu (large population), A hi tirheni Mqekwa farm and Macena farm (large total dynamic head). On the other hand, moderate peak power requirements and solar panel areas were calculated for Mbhedle, Matsambo Ngamba farm and Duvadzi farm.

Groundwater samples of all water sources were collected and analyzed in the laboratory to determine fitness for use. The results are presented in Tables S1 and S2 (Supplementary Materials) and they were compared to the South African National Standard SANS 241 of 2015 to determine the water quality fitness for domestic use. The figures in red in Tables S1 and S2 indicate values of determinants that are not within the SANS 241 thresholds. In general, groundwater quality is not fit for domestic use as is, and some water treatment will be essential. Water quality is fit to marginally fit for agriculture, based on the South African Water Quality Guidelines [61] for agricultural use. Any build-up in groundwater and soil salinity should be monitored. Whilst pH values are within the prescribed standards for all water sources, the sites in the villages of Mbhedle, Matsotsosela, Matsambo Ngamba farm, A hi tirheni Mqekwa farm and Duvadzi farm have elevated electrical conductivity (EC), in particular due to elevated Na and Cl.

Groundwaters in the proximity of villages (draining water from villages) have particularly high NO_3 levels beyond the legal standard (<48.7 $mg \cdot L^{-1}$ NO_3). This is especially the case for the villages of Mbhedle, Mayephu, Mzilela, A hi tirheni Mqekwa farm and Macena farm. The spike of >200 $mg \cdot L^{-1}$ NO_3 concentration at borehole H14-1815 in Mayephu is due to the vicinity of an animal kraal (<30 m). In addition, Matsambo Ngamba farm, A hi tirheni Mqekwa farm and all sites in the villages, except Mzilela, exhibited high concentrations of Total Organic Carbon (TOC > 10 $mg \cdot L^{-1}$) at the end of the rainy season (Table S1). By far the best water quality source is the water retained in the sand alluvial aquifer of the Molototsi River (Nhlambeto farm at Dzumeri) (Tables S1 and S2). This confirms previous results that water quality in the sand banks approaches rainwater quality as it originates from direct vertical recharge via rainfall [62]. All parameters were within the standard limits, except color due to high turbidity. However, elevated concentrations of Al and Fe were found in the sand banks aquifer, especially in May 2022, and this needs to be investigated further. Elevated Mn beyond the aesthetic threshold (100 $\mu g \cdot L^{-1}$) was found in Mbhedle and at Matsambo Ngamba farm (Tables S1 and S2). In general, these findings make it imperative to treat the groundwater for drinking water purposes and this has implications on the capital investment and operational costs.

4. Discussion

The originality of this study lies in the fact that solar-powered groundwater pumping schemes and MUS need to be adapted to very site-specific environmental and socio-economic conditions. In the context of South Africa, in particular in Greater Giyani Municipality in Limpopo, the primary challenges are climate change with increased frequency of drought and water scarcity, poverty and unemployment, and the lack of water reticulation and grid electricity systems, coupled with a current national energy crisis. Solar-powered groundwater pumping and MUS schemes are adaptation strategies that may address all these challenges. Similar international research has been conducted in the Youssoufia Province of Morocco through the project IMAGINE, where water–energy–food nexus adaptation interventions were established by empowering poor rural communities [63]. The approach is also consistent with the Adaptive Investment Pathways (AdIP) proposed by [64] for irrigation development in Sub-Saharan Africa. They argued that large investments in irrigation schemes could be less efficient than smaller developments that are consistent with the sparse nature of small-holder farming and solar energy resource availability. Ref. [64] provided a case study of irrigation from ephemeral sand rivers.

The sites in the current study have boreholes that are either connected to a national grid power line or are powered through the use of fuel (diesel or petrol) in order to pump water. The establishment of boreholes has helped communities with drinking water supply and small-scale farmers to produce more crops to sell to the locals and markets. However, since their crop produce increased, the constant rise in the prices of traditional sources of energy brought challenges as it became expensive to pump water. These challenges also affected the community at large as the locals cannot afford to buy their own fuel or electricity for water pumps and the local government is not always prompt in assisting and subsidizing the communities by supplying them with electrical power or diesel. The opportunity emerged to consider alternative power sources, which can be efficient for pumping water and meet the water needs of the community at much lower costs. Solar water pumps are suitable for use in rural areas, and they are cheaper to use as compared to diesel and electricity.

Gaining the approval/support from the community is important for any project prior to its implementation. The social aspects of the transition to solar-operated systems are critical as communities need to play a bigger role in the management, maintenance and security of such systems compared to bulk supply and conventional systems. Likewise, there is a need for the full engagement of the water services authorities, especially if there is an intention of them taking over developments or if there is the anticipation that water governance institutions adopt solar-powered systems more widely within rural settings. Failing this is likely to have considerable consequences for broad adoption and for the emergence of funding models. The case study sites lend themselves very well to build on current infrastructure, e.g., boreholes and water reservoirs have been established, pumps and pipelines are operating, etc. Financial constraints pertaining to the high cost of fuel and electricity appear to be high on the community agendas, which justifies the capital investment in renewable energy sources to power the water supply systems. This can be a cheaper option in the long run. Most villages do not have water on tap or the accompanying infrastructure, which makes the need for water supply interventions urgent. Likewise, the support of regulatory authorities is essential in the issuing of water and environmental licenses (government authorities) and for land use or permission to occupy land (traditional authorities).

From the geotechnical feasibility perspective, the area is moderately suitable for the utilization of solar energy with average solar irradiation of 4.9 kWh/m^2/d (photovoltaic power output of 1589.3 kWh/kWp) and a large number of sunshine hours per day. There is potential for intensive agricultural production and value-added products with access to both informal and formal markets in the urban areas of Giyani (~50 km north) and Tzaneen (~70 km south-west). Other economic development activities could relate to spin-off businesses. Because of the current lack of bulk water supply, MUS systems would definitely benefit livelihoods and cultural activities, and improve sanitation, hygiene and health. Although formal waste collection sites do not exist in the area, including e-waste, batteries, plastics, etc., the volume of waste generated by the solar-powered pump systems is sufficiently small to be stored at localized sites and it does not represent a problem.

The implementation of solar-powered groundwater pumping systems may result in beneficial impacts on water security, agricultural impact, involvement of local communities and gender equity. However, it may have negative impacts on natural resources, especially if over-abstraction of groundwater occurs, which needs to be controlled through sustainable management of groundwater. Groundwater storage should be sufficient to sustain water supply during periods of drought as a reserve, however groundwater recharge will be essential from occasional flood events to render abstraction sustainable. Shallow groundwater yields are moderately high in the area, however one of the main constraints is the long-term sustainability of groundwater abstraction and the risk of over-exploitation of groundwater resources. In previous research conducted by [62], it was estimated that a 100 m reach of the dry Molototsi River stores 2700 m^3 of water in the sand banks. This is sufficient to irrigate ~0.66 ha of vegetables for one season, assuming irrigation water requirements of 4000 m^3·ha^{-1}. A monitoring system needs to be put in place in order to keep track of groundwater levels as well as groundwater quality through a physical, chemical and microbiological monitoring program. Technical capacity for community monitoring needs to be built.

The financial viability of solar energy was demonstrated by comparison with traditional energy sources in the case study examples. While solar energy can provide cost savings of >ZAR 400,000 compared to grid electricity over a life cycle of 25 years, diesel-powered systems are not financially viable. The constraint is the high capital costs of solar energy. It is therefore likely that the capital investment will have to be subsidized by rollouts by the government or donors. The operation and maintenance of the water supply scheme according to the MUS principles should be handed over to the community under the guardianship of the water services provider (local authority). The participation and buy-in of the community and local government is therefore fundamental as these entities will be co-owners of the systems and be responsible for the operation and maintenance in the long run. Feasible financial mechanisms for the operation and maintenance were identified to be leasing, cooperatives, informal saving groups and pay-per-use. A full review of financial models and operating options is pertinent in this regard.

The sizing of the system is very site-specific, and this was designed with the SPIS tool [50] based on biophysical information, specific borehole yields and aquifer characteristics, required pressure heads and water requirements. It is in the same order of magnitude as sizes and designs that were found in the literature [17]. Peak power requirements and the design of solar panel arrays can be further adjusted based on the equipment specifications and availability on the market from suppliers and manufacturers as well as photovoltaic arrays arrangements. The pipeline layout, pipe diameter and installation of tanks, including the use of booster pumps to ensure that enough water pressure is delivered, can all be adjusted at the time of implementation in order to secure an optimal design and final set-up. A large number of scenarios can be constructed for different cases: multiple-use water supply for irrigation and drinking water, different irrigated areas, crop rotations, population numbers, hydrogeological settings, groundwater yields and storage, configuration of solar panels, battery and hybrid systems, pump specifications, conveyance pipe layout and size, volume of storage tanks and financial inputs and results. However, it is deemed that the examples provided for the nine case studies establish a good starting point and realistic results on the feasibility of implementation of solar-powered groundwater pumping systems.

The quality of water in the sand bed river aquifers is excellent because recharge occurs directly from rainfall [62]. However, shallow groundwater quality at the sampling points is not always fit for drinking purposes. Occasionally, elevated values of n (above levels recommended for human or cattle consumption) are possibly due to activities in villages, which points out potential risks of contamination of groundwater resources in villages that do not have a sanitation system. Water quality needs to be monitored by accredited laboratories according to standards and protocols, especially for drinking water purposes, to determine any potential risks from all non-point and point pollution sources, in particular microbiological contamination. Water purification/filtration systems, likely in the form of small reverse osmosis plants, need to be installed to ensure that water quality does not pose any risk, in particular to human health. This implies increased capital and operational costs and may impact on the financial viability of the system, the market potential and especially the finance deployment mode. In the case of contaminated samples, an emergency plan for a system shutdown should be put in place. Water quality is moderately fit for agricultural water use. Filters need to be installed on the mains to ensure the longevity of drip-irrigation systems. Marginally high salinity levels are not expected to affect yields of salinity-tolerant crops, soil salinization and permeability or cause toxicity effects and major impacts on the overall ecosystem through leaching and non-point source pollution. However, salinization needs to be monitored in the long term.

Lastly, solar-powered groundwater pumping systems are to be seen as an emergency intervention and as an adaptation measure to climate change to improve well-being, health, absenteeism from schools and drudgery on women and girl children associated with water collection. These systems are not meant to replace bulk water supply; however, they can be integrated with bulk water supply where possible. A major infrastructural project is under way in the area to transfer water from the Nandoni Dam in Vhembe District to Greater Giyani Municipality as bulk water supply [65]. Bulk water supply is meant to provide water on tap in households, but not necessarily water to small-scale farmers. The implementation of solar-powered groundwater pumping systems and MUS is to be seen as a "no regret" action because it will augment the water supply and it can provide water during periods of drought and breakdowns once the bulk water supply system has been put into operation. Such systems also offer a back-up in the event of power outages and power grid failure and are therefore a valuable source of system redundancy in resilience-building endeavors.

5. Conclusions

The feasibility study indicated that the adoption of solar-powered shallow groundwater pumping systems and MUS is viable in terms of solar irradiation, costs of energy, agricultural productivity, market potential and groundwater availability for small-scale water supply systems in Greater Giyani Municipality. It may result in beneficial impacts on water security, spin-off businesses, involvement of local communities and gender equity. A water quality monitoring program needs to be established, based on adequately frequent sampling and analyses for physical, chemical and microbiological vectors at control points, especially for drinking water. Regular monitoring of groundwater levels (e.g., monthly) is also strongly recommended to avoid excessive drawdown of groundwater tables beyond sustainable recovery levels.

Typical case studies for small-scale water supply systems indicated peak water requirements ranging from 28.8 to 58.9 m^3/d, peak power requirements from 1.2 to 3.4 kWp and required solar panel surface areas from 8.0 to 22.3 m^2. In terms of securing satisfactory water quality, filters should be used for irrigation water supply, whilst water purification (small reverse osmosis plants) is essential for drinking water supply, which increases the capital and operational costs. Feasible financial mechanisms were identified to be leasing, cooperatives, informal saving groups and pay-per-use. However, it is likely that the solar-powered systems will have to be funded and the operation and maintenance subsidized through donors/governmental institutions, at least during a piloting phase. The involvement and commitment of local government and communities are fundamental to ensure the operation, maintenance and long-term sustainability of the systems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app13063859/s1, Table S1. Results of laboratory analyses of groundwater samples collected from all water sources at the case study sites in May 2022, and compared to the South African National Standards 241 for drinking water quality; Table S2. Results of laboratory analyses of groundwater samples collected from all water sources at the case study sites in November 2022, and compared to the South African National Standards 241 for drinking water quality.

Author Contributions: Conceptualization, N.J. and B.P.; methodology, N.J., M.M., A.W. and B.P.; software, N.J., M.M. and A.W.; validation, N.J., E.M., K.P., B.N., G.M. and D.d.T.; formal analysis, N.J., M.M. and A.W.; investigation, N.J., M.M., A.W., E.M., D.M., B.P., V.M., Z.S., K.P., B.N., G.M. and D.d.T.; resources, N.J., B.P., V.M. and Z.S.; data curation, N.J., M.M., A.W. and E.M.; writing—original draft preparation, N.J.; writing—review and editing, E.M., D.M., B.P.; visualization, N.J., M.M., A.W. and E.M.; supervision, N.J., D.M., B.P., V.M., Z.S., K.P. and D.d.T.; project administration, N.J., B.P., V.M. and Z.S.; funding acquisition, N.J., B.P., V.M. and Z.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, grant number 81270515 and Water Research Commission (C2021/2022-00718).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting reported results are available from the authors.

Acknowledgments: The authors thank the South African Department of Environmental Affairs, Forestry and Fisheries for the overarching leadership, the stakeholders, government officials, community representative and members, and farmers who participated in the consultative workshops that took place in Greater Giyani Municipality during September 2021. The Agricultural Research Council is thanked for providing weather data.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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