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WEF Nexus Phalaborwa

Authors:
Daan Berbé (4720733)
Aafje Houben (4732677)
Max de Jonge (4688643)
Houxuan Zhang (5818664)

Supervisors:
Dr. Mike Buxton
Dr. Feven Desta
Dr. Fransje Hooijmeijer
Isabel Recubenis Sanchis
Tahira Toffah

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Abstract

This multidisciplinary report explores the transition potential of the Phalaborwa region, South Africa, from a mining-focused economy to one that integrates sustainable water, energy, and food (WEF) systems in a post-extractive setting. Set within a semi-arid climate with significant resource challenges, the study assesses WEF capacities to propose strategic, sustainable development solutions. Analyzing critical issues like water scarcity, renewable energy potential, and soil management, the study presents frameworks for sustainable agriculture, water management, and energy solutions to support post-mining economic resilience.

Through a multidisciplinary methodology that integrates engineering assessments and urban planning, the report addresses critical biophysical resource issues. The findings emphasize the region's unique resource interdependencies, outlining frameworks for post-mining development that strengthen resilience to climate pressures and resource limitations. Ultimately, this study provides actionable insights for creating a balanced, sustainable future for Phalaborwa and the surrounding area. Although the study proposes frameworks that could inform similar transitions in other semi-arid, resource-constrained regions, it also emphasizes the importance of addressing the unique complexities of each area to ensure that solutions are appropriately tailored.

Chapter 1

Introduction

In 1904, Hans Merensky, son of a South African missionary and a trained geologist from Germany, discovered apatite at Loolekop in Phalaborwa. Apatite, a phosphor-bearing mineral, acts as commodity for fertilizers and was thus immensely valuable in the dawn of modern welfare-states with high demand for food. Merensky, however, considered his samples to be of little interest. The grades were low and a potential apatite reserve bore no competition to the high-grade phosphate mines of Morocco. Moreover, the Lowveld's red bush-willows and mopane trees made further exploration difficult, not even mentioning setting-up a mining venture so remote – with 350 kilometers north-east of Johannesburg and no train track nor proper road apt for ore freight, the only image of Phalaborwa that remained in Merensky's mind was the peculiar sample he discovered: a boot-shaped apatite sample. What is the reason, the reader asks, that fifty years later in 1954, the same site was home to the world's largest copper reserve, which was on the verge of being exploited. It can be speculated that, without the nearby Kruger Park and its wildlife tourism, mining activities might never have occurred in the area. Following in Merensky's footsteps, geologists from Witwatersrand, such as Du Toit and E.T. Mellor, traveled to Phalaborwa mainly for its ivory tusks, but, since unexplored lands were around the corner, also for its minerals. Mining exploration developed alongside the wildlife tourism and with the increasing knowledge of Phalaborwa's geology it was only a matter of time until mining engineers were introduced to the region. A first venture tried from 1930 to 1934, but failed and went bankrupt. Hans Merensky, however, recalling his apatite boot, figured eleven years later in 1945 that Phalaborwa was of great importance to South-African's future. During the war Morocco's high grade phosphates were shipped of to France and left South-Africa helpless. Phalaborwa's low grades became suddenly high grades, due to geopolitical dynamics, and the Lowveld evolved into a key region of South Africa that provided fertilizers for the whole of Southern Africa. With the rise of the mine came the rise of Phalaborwa: "the mining city of the future".

This history is not solely brought up to provide a background on the mining business in Phalaborwa, or, if you like, the prosperity created by the industry. Granted, the region's poor state changed within half a century and that is perhaps the lesson to be learned from Phalaborwa past. However, the largest lesson that speaks from Phalaborwa's past is not *who* or *why* it changed, rather *that* it changed. Change requires potential and potential is thus to be discovered and even as simple information as one sample of apatite can change the future of a region. Hence, within the scope of this report it is unnecessary to continue to tell the mine's history and to dwell on the mining engineering business: the population grew, political regimes rose and fell and the mine expanded to an enormous volume both open-cast and underground. Instead, this report speculates on the future change and potential of the region, for the potential is there, lest it remain undiscovered. Seventy years later, in 2024, the city of Phalaborwa and the mine have developed in close connection with one another. The reality is that the mine will likely close half-way trough the century, whether in 2040 or 2060 doesn't necessarily matter. What matters is the 'aan zekerheid grenzende waarschijnlijkheid' (probability bordering on truth) that the fate of Phalaborwa won't be in the hands of mining. What started in 1904 with Hans Merensky ends, let us say, in 2054.

In Merensky's legacy, the scope of this study was to find so to speak another boot-shaped apatite, a reason to develop a new future for Phalaborwa, to discover its potentials and challenges given the region's *semi-arid climate condition.* This time, however, it's not a mining future, but something different. To accommodate to the qualities of the authors, three students in mining engineering and one student in urban design, the report primarily focuses on the *biophysical* and *socio-cultural.* Topics such as government and economics are not excluded due to ignorance or lack of insight, but rather, in the humble opinion of the authors, due to their limited knowledge on these topics. In clear terms, with the scope primarily focused on biophysical and socio-cultural dimensions, this study considers each node of the water-energy-food (WEF) nexus to determine what sustainable limits or opportunities exist. *What is the carrying capacity of WEF systems in semi-arid rural regions?* Water availability, for instance, is a primary consideration in such a dry region, where every usage impacts other sectors. This leads to further questions: How might water resources be used to support future uses without wholly depleting the sources? Energy production, too, demands re-evaluation, especially considering Phalaborwa's abundant solar exposure. The insights in the carrying capacities by itself lead to the opportunities and answers *what WEF-based infrastructures, techniques, and relational spaces are key to this transition, and how?* For example, is agrivoltaics, a combination of agriculture and photovoltaics, viable for renewable energy without competing with the agricultural needs of land? In Phalaborwa, where semi-arid conditions limit the potential of the land, questions of sustainable resource use have become central. Mining and extraction dominate the landscape. Yet these activities directly impact the region's carrying capacity, that is, the reserve of a biophysical property, such as water, energy, and food. For instance, water used in mining processes is often collected from local rivers, making it unusable for domestic needs or other industries.

Thus, the reports answers *how the local carrying capacity of WEF systems in semi-arid rural regions can be the starting point to transition from extractive to non-extractive futures*, that is, to explore a shift of Phalaborwa and the region stretching from the Drakensberg escarpment to the Kruger Park *from mining to mine-closure to post-mining.*

Chapter 2

Project Approach and Structure

2.1 Methodology

The approach to exploring Phalaborwa's potential is presented here.

Since the conducted study encompassed multiple disciplines with varying methodologies, some chapters adopt an engineering approach, while others focus on an urban planning approach. The engineering methodologies are in detail explained in the respective chapters on water, energy, and food, while the methodology for urban planning is presented in Chapter 6. Here, the study's overarching approach is presented.

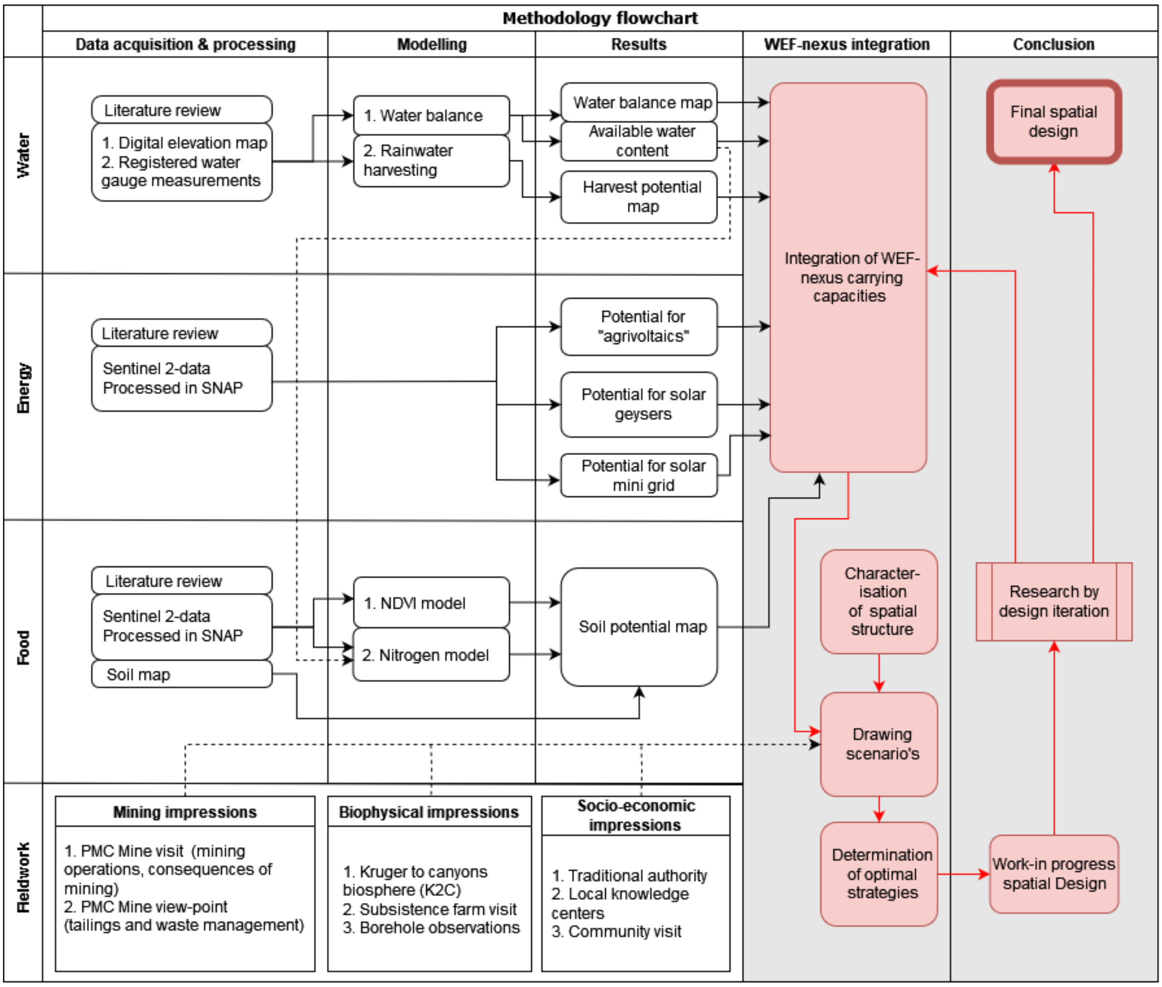


Figure 2.1: Methodology flowchart. Black arrows indicate the engineering workflow step. Red arrows indicate the "research by design" steps

The methodology of this project is perhaps not as straightforward, as it integrates both scientific-engineering and urban planning approaches in a multidisciplinary framework. The flowchart (2.1) illustrates the combined approach of the study: the first three columns represent the engineering methodology, while the last two columns represent the urban planning methodology. (Readers are reminded that the flowchart is a simplified illustration and wishes not to represent a strict separation of methodologies. While both methodologies are intertwined, some division was necessary to show the primary approaches used in different parts of the study for clarity.)

From an engineering perspective, a sound research demands an overview of the available and gathered data and a reproducible method. This means that acquired data is strictly defined and its limitations stated. Only on the basis of such an univocal approach the engineering methodology is worth the predicate "scientific". This demand is fulfilled in researching the carrying capacities of water, energy and food (columns 1 to 3). However, this project is not solely written from an engineering perspective, since demanding scientific univocality would limit the aim of this project. After all, the aim, as defined above, is to research how the carrying capacities can be the starting point of a transition. Said *transition* cannot be answered univocally, since the nature of transition is complex and equivocal. Exactly here the role of the urban design approach guarantees that the research aim can be answered. The demand for univocality in urban design is fulfilled by a methodology known as "research by design". This encapsulates the process of researching a certain topic, a constrained area, by providing solutions to problem whilst not fully grasping its definitions and limitations. Strictly speaking, the urban design approach is less "scientific", since it disregards aspects of the problem the scientist deems necessary for a sound starting point of the research. However, the urban designer answers to this critique that it's primarily the approach that is affected by this "research by design" – the final result is just as sound and scientific as the work of an engineer. In practice, research by design involves repeatedly applying solutions to the study area, with each previous solution serving as a foundation of knowledge for developing the next. In such fashion of iterative problem-seeking and problem-solving an optimal design is discovered (see column 4 and 5). The engineer interprets this approach—perhaps not fully correct—as "trial and error" and finds it useful, especially upon realizing that the engineering method alone would not allow him to draw conclusions for a study area this large and a system so complex.

In summary, this study used an approach that merges two distinct methodologies: an engineering methodology and an urban planning methodology. The engineering approach studies the carrying capacities of water, energy, and food resources, while the urban planning approach integrates these findings. More importantly, the study applies a “research by design” approach, by continually refining and updating the research on water, energy, and food in combination with the work-in-progress spatial designs (as indicated with the line from "research by design iteration" to "integration of WEF-nexus carrying capacities)".

2.2 WEF-nexus

The study was conducted within the scope of the WEF-nexus. The term was already employed above, but not properly explained, so a short introduction to the WEF-nexus is provided here: The Water-Energy-Food (WEF) Nexus is a framework that helps study the connections between water, energy, and food systems. It assumes that these three resources are interconnected, and changes in one can affect the others. In the case of Phalaborwa, for example, water is needed for agricultural activities. In turn, energy is required for water extraction, treatment, and distribution, and is necessary for food production processes, such as as irrigation and food processing. Food production also relies on water and energy, namely for irrigation, harvesting, or transportation. The WEF Nexus, thus, perceives a study area equivocally by considering water, energy and food not individually but as a system.

2.3 Study area

The study area is situated in Limpopo, South Africa, more precisely in between the cities of Tzaneen and Phalaborwa (see Figure 2.2). The region is characterized by a semi-arid area with very hot summers, hot winters, and seasonal rainfall mainly during summer. Water is limited, and droughts are frequent. Nearby Tzaneen, situated along the Drakensberg escarpment, has a wetter climate with higher rainfall, supporting agriculture like fruit and vegetable farming. The escarpment divides the dry Phalaborwa region from the more fertile Tzaneen area.

The local population in Phalaborwa relies heavily on mining, while Tzaneen's economy depends more on agriculture. Water supply is a shared challenge, as both areas need water for their main industries. Understanding water availability and usage is critical to support both the farming in Tzaneen and mining in Phalaborwa.

> *Note: although this study defines a specific area of focus, the individual assessments of water, energy, and food vary slightly from this area due to reasons that will be explained in the methodologies of each respective topic.*

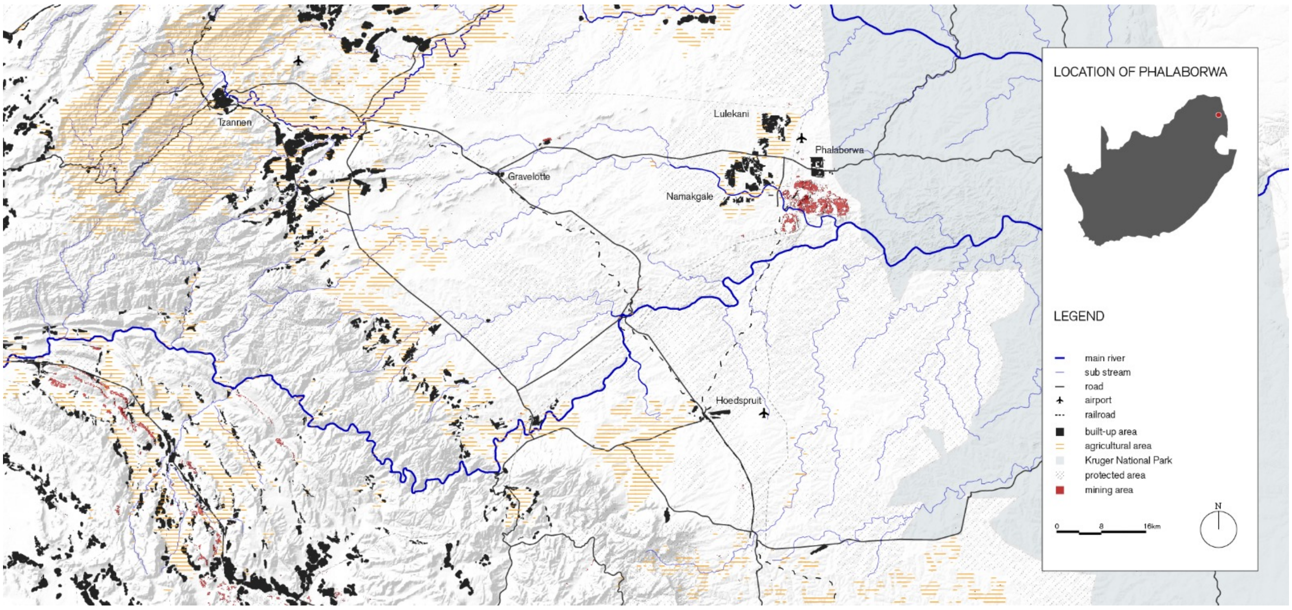


Figure 2.2: Study area

2.4 Report structure

The table of contents provides already a good overview of the report, however, to help the lazy reader the structure is presented here again.

The report is structured into several sections. First, the three main resource chapters elaborate on the biophysical carrying capacities: Water, Energy, and Food, each examining the current status, challenges, and potential strategies for dealing with these resources in the study area. For example, the water section includes a review of the status quo, experimental studies on water balance and rainwater harvesting, and water-saving strategies. Nex, the WEF Nexus and Vision chapter integrates the findings from the water, energy, and food sectors, proposing spatial strategies based on current scenarios and the biophysical analysis. The discussion and recommendations section explores future research and next steps, followed by the conclusion, which addresses the main research questions. Finally, the reflection section discusses insights from the field trip and the learning process from the perspective of the students involved.

Chapter 3

Water

This chapter studies the critical state of water resources in Phalaborwa and the B7 catchment area, assessing both current availability and the pressures from competing uses, climate variability, and quality degradation. It includes an experimental water balance study and delves into the potential of rainwater harvesting as a supplementary source. The chapter concludes with strategies for sustainable water management from a WEF-Nexus point of view.

3.1 A Review of the Status Quo

3.1.1 A Resource Under Pressure

Water resources are critical to sustaining life, enabling economic development, and preserving ecosystems. The Phalaborwa region, located in the Limpopo Province of South Africa, is characterized by its hot semi-arid climate (BSh - Köppen climate), and is home to significant mining activities, agriculture, and natural conservation areas, such as the KNP (Kruger National Park). These diverse sectors demand considerable amounts of water, creating competing uses and putting pressure on the region's finite water resources. Climate variability and changing rainfall patterns add further complexity to water management challenges in the form of droughts and flash-floods. Thus, balancing these competing water needs within the constraints of available supply is critical for the long-term sustainability of the region's ecosystem, economy, and communities. The study area for this chapter is restricted to the B7 secondary catchment, as can be seen in figure 3.1. The B7 catchment was chosen due to it forming a natural boundary for surface water concerning the Phalaborwa region.

The Phalaborwa region faces serious challenges related to water. From unregulated borehole completions for subsistence farming to infrastructure related issues due to illegal tapping from water pipes. The status quo should raise concern with anyone interested in a save and legal future for the Phalaborwa region. The regional and local government are aware of the stress the water resources are experiencing, although a detailed quantitative analysis of the biophysical system has not been conducted. For successful water management it is essential that a trusted baseline of the environment's carrying capacity is in place such that decision making of all scales can be tested against a water budget. This should stimulate a more longue duree and sustainable approach to decision making in the region.

The Phalaborwa area is vulnerable to droughts, which have become more frequent and intense due to climate change [12]. Drought conditions have impacted the region's water resources, particularly surface water and groundwater supplies. The region experienced prolonged periods of water stress due to reduced rainfall and rising temperatures, which resulted in lower river flows and reduced dam levels. The Olifants River, a critical water source for Phalaborwa, has seen reductions in flow during drought years, which has placed additional pressure on the water supply for both domestic and industrial use [52].

Water quality in the Olifants catchment has been declining due to increasing anthropogenic pressures, including agricultural runoff, sewage overflow, mining activities, and artisanal gold mining. These activities contribute contaminants such as nutrients, metals, and pathogens, impacting both local and downstream ecosystems. Conflicting literature on quality and availability (mainly groundwater) raise the complexity of finding suitable solutions for the Lower Olifants watershed. Not only the lowveld, but the entire Olifants watershed is currently facing significant stress due to increasing water demands. The catchment is therefore considered 'closed', meaning that it consumes more than it produces. Around 500 million cubic meter of water is being imported annually from the Crocodile and Vaal catchment to support Eskom power stations and mines in the Highveld, often at high costs. If the energy industry were to relocate, the feasibility of continuing these water imports would be seriously in doubt [20] [21].

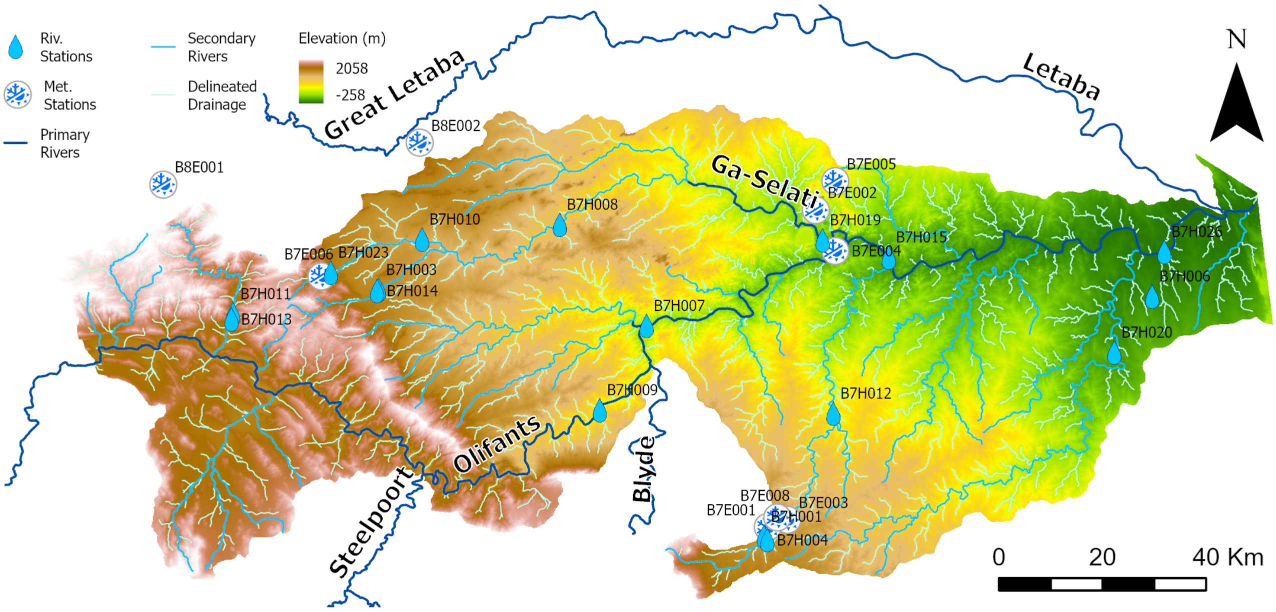


Figure 3.1: Extent of catchment zone B7, including the location of measuring stations

3.1.2 Groundwater

Groundwater availability in the Olifants catchment is compartmentalized due to varying hydrogeological rock formations. The DWS reconciliation report identifies several areas with stressed aquifers, where abstraction and baseflow exceed recharge, including the KNP catchments where groundwater supports both community water needs and wildlife [19]. Despite these challenges, groundwater remains the only reliable water source in many regions, though new abstraction will likely suffice only for domestic and livestock needs in small villages. High-yield development opportunities are limited to karst/dolomite aquifers along the escarpment.

The study area lies primarily within the Lowveld Groundwater Region (Region 19) as described by Vegter [76], dominated by Precambrian gneisses and granites. A vast network of faults and dykes are present in the area, which originate from a complex billion year old structural history. The Makhutswi Gneiss (3.2 Ba) underlies much of the Lowveld region, and the aquifer is characterized by fracturing and weathering. Median borehole yields are under 0.1 L/s, with only 21% yielding more than 1 L/s. Weathering depths are below 40 m in 90% of boreholes, with only 6% showing weathering and fracturing beyond 55 m. Roughly 61% of boreholes reveal weathered zones less than 20 m thick, and in 81%, the combined weathered and fractured zones are under 40 m. In 68% of cases, water is intercepted within the first 30 m, with additional presence along fault zones and, to a lesser extent, at dyke contacts. Boreholes rarely encounter water below 40 m. The recharge rate is estimated at around 12 mm/year [17], and groundwater baseflow is effectively 0 mm/year, as most/all recharge is lost to evapotranspiration from shallow groundwater sources [79]. Statistical analysis on existing boreholes conducted by Vegter [76] found that chances of striking water are not altered by the presence of geologic dykes. The study shows that dykes should be considered integral to the surrounding hard rock rather than as distinct hydrogeological features. Their water-bearing properties can vary along their length and should not be seen strictly as barriers or conduits. The likelihood of encountering water at dyke contacts depends on the weathering and fracturing of both the country rock and the dyke below the groundwater level. The National Groundwater Archive (NGA) indicates that while a significant number of boreholes are registered, most records consist solely of geographic coordinates, with minimal data regarding water levels or yields. A notable concentration of these boreholes is found in former townships such as Namakgale, where there is considerable advertising for borehole drilling services. This trend is leading to unsustainable groundwater abstraction practices. The author's own experience was that many recent boreholes were also absent in the NGA database, exacerbating the problem further.

In the western region of the study area, irrigation farming occurs, likely utilizing both surface and groundwater sources. However, groundwater usage remains largely anecdotal, with little information available on the extent of use and levels of abstraction. To address these concerns, it is imperative to initiate a comprehensive project aimed at assessing groundwater use for irrigation. Over-abstraction of groundwater resources could have significant repercussions for both local water supplies and the regional economy. Moreover, there are potential adverse effects on water availability for rural communities, making this assessment essential for sustainable water resource management [18].

Generally, groundwater potentials are highly uncertain and a variaty of results have been reported on the matter as seen in table 3.1. This table shows estimates for the entire Olifants watershed (B).

Table 3.1: Groundwater Abstraction/Availability Estimates for Olifants WMA [19]

Year	Exploitable/Available Yield (Mm^3/a)	Abstraction (Mm^3/a)
1980	-	170
1995	180	100.6
2000 (DWAF)	99	-
2001 (Seward)	-	183.3
2003 (Van Vuuren)	287.4	-
2007 (AGES)	70	217
2007 (GRAII)	468.9	100,5

Malmani Dolomites

High borehole yields are reported in dolomitic regions [16]. The relatively undeveloped Malmani dolomite aquifer, which follows the escarpment's topography, presents a potential groundwater resource. However, concerns regarding the sustainability of increased abstraction due to contamination risks and long-term viability are substantial. Similar aquifers in the catchment have demonstrated that over-exploitation is a critical issue. The Malmani dolomites possess a positive groundwater balance of approximately 60–90 million cubic meters per year, with 15 million cubic meters allocated for the Lower Olifants [19]. Further studies are needed to assess the impacts of increased abstraction, especially since numerous springs contribute to the Lower Olifants watershed. Currently, the region is focused on developing this aquifer to support local water needs. Recent studies have characterized the Malmani dolomites as highly heterogeneous and anisotropic, with unconfined to semi-confined aquifers believed to be compartmentalized by doleritic dykes. Although this idea conflicts with Vegter's conclusions, it remains plausible due to differing interactions between the dykes and the dolomitic host rock compared to the gneisses. Yields of over 10 l/s have been reported near large regional fractures, with preliminary sustainable abstraction estimates at 29 hm^3/a [47].

3.1.3 Surface water

Surface water in the Olifants catchment is both vital and vulnerable due to variable flow regimes, season fluctuations and anthropogenic activity. The catchment experiences extreme seasonal variations, with peak flows occuring during the summer season as can be observed in table 3.2. Conversely, large portions of the watershed can run dry during the winter months as seen with B7H008. Station data was obtained from the national database [69]. Within the Olifants catchment, surface water is managed through a series of dams, weirs, and natural pools, which play a critical role in stabilizing water availability for both human and ecological needs. Due to their ability to slow or increase flow if necessary. However, the system is under strain; upstream abstractions frequently exceed sustainable limits, leading to low downstream flows that impact the KNP and other downstream ecosystems, especially in years of drought. Consequently, conservation efforts and regulated surface water management are key priorities to ensure sufficient flow for both people and wildlife. A number of smaller dams also occur in the Olifants catchment and have a significant impact that is disproportionate to their sizes because they most often are not built to the same standards and specifications as the bigger dams [20].

Mean annual runoff, which is the naturalized flow from the surface into waterways was compared between 1920 and 2004. The tertiary catchments B71, B72 and B73 had a respective change of -11.1%, -5.6% and 8.9%. Significant impact stems from forestry, alien vegetation, irrigation and farm dams [20]. The data for the Lower Olifants sub-catchment indicates that while there is potential for exploitable surface water, challenges exist due to a lack of suitable dam sites and the distance from water demand centers. Geographic and infrastructure constraints could limit development, impacting overall water supply management. Additionally, enhancing gauging stations, as recommended, would yield improved data for more effective resource management in this area.

As of 2004, the only ecological release in the Water Management Area (WMA) consists of a minimum flow of 0.54 m^3/s (17 million m^3 annually) from the Phalaborwa Barrage to the lower Olifants River, which flows through KNP. An agreement has been made with the Resource Directed Measures (RDM) office of DWAF regarding ecological flow releases from the Flag Boshielo Dam. The dam's design includes the necessary structures to meet a maximum ecological flow requirement of 18 m^3/s [16]. While further data may exist, its was not found during the research.

Table 3.2: Flow Rate Statistics (m^3/s)

Station	**Record**	**Season**	**Count**	**Mean**	**Std**	**Min**	**25%**	**50%**	**75%**	**Max**
B7H019	'88-'23	Summer	95.0	46.55	77.09	0.067	2.74	14.75	48.72	305.41
		Winter	93.0	0.85	0.96	0.072	0.27	0.74	1.24	8.76
B7H015	'87-'24	Summer	107.0	299.44	302.21	6.01	117.96	224.78	404.79	1785.85
		Winter	102.0	22.05	33.51	0.56	6.86	12.33	22.27	252.07
B7H007	'67-'24	Summer	140.0	235.24	240.12	7.97	68.67	132.10	322.34	1104.90
		Winter	140.0	15.36	19.05	2.33	6.10	10.58	20.10	201.22
B7H008	'56-'99	Summer	120.0	48.34	209.02	0.00	0.00	1.50	16.14	2149.20
		Winter	120.0	0.49	2.90	0.00	0.00	0.00	0.13	30.90

3.1.4 Water quality

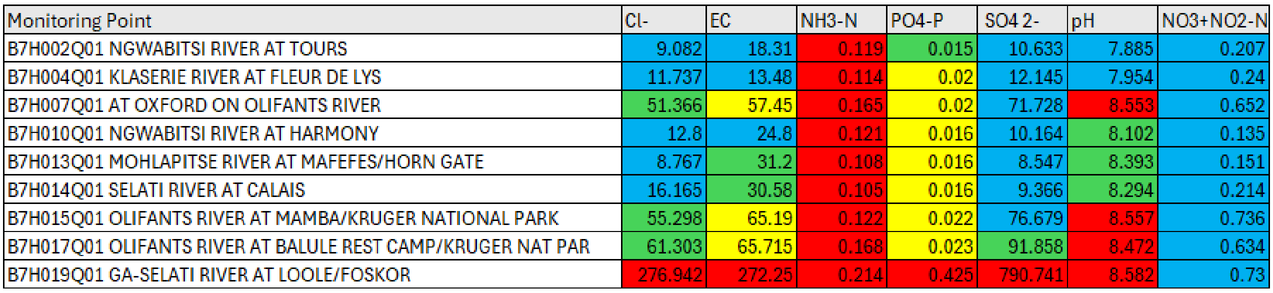
Next to the stress on the water resources, the water quality of the region's surface waters is deteriorating due to anthropogenic activity [75] [50]. The Ga-Selati river is a key contributor to the pollution of the Olifants river due to unwitting use of fertilizers, overflowing sewage, dysfunctional waste water treatment works and large scale mining activities in the Phalaborwa Igneous Complex (PIC). Together this introduces salts, metals, nutrients, and E. coli into the river system. Water samples from the lower Ga-Selati River consistently show the highest levels of phosphate, sulfate, and salinity in the lower catchment. While sulfate and salinity levels have been gradually decreasing, phosphate levels have continued to rise since data collection began around 1990, contrasting with improvements seen in other parts of the catchment [63]. Although acid events have been reported at the site, pH data indicate that the water remains alkaline but stable over time. Various toxic elements, including metals, pesticides, and herbicides, have been detected in both water and sediments. The effects of water entering the Olifants river from the Ga-Selati River are evident downstream, impacting the KNP and extending into Mozambique [50]. However, these levels decrease after dilution with Olifants river water [63]. According to sources from the locally operating K2C Biosphere NGO; The Blyde river, a tributary of the Olifant's river, which was considered a class 0 'pristine' river dropped to a class 2 'marginal' in mere years due to artisanal gold mining by Zamazamas. This activity is not only detrimental for the water quality of the river system, but also losses in sales, tax revenue and royalties due to the illegal nature of the mining hinder development of the area. Pollution comes not only from illegal mines but also from legally operating ones. This is not surprising, as an interview with the environmental superintendent at PMC revealed that the tailings storage facility was built without specific considerations, likely including a lack of design for preventing toxic leaching.

Sediment loading in the river is a significant concern, primarily due to degraded lands in the middle catchment. This sediment affects water quality and has multiple impacts on river ecosystems. When sediment is deposited in reservoirs, it reduces their storage capacity, as observed at the Phalaborwa Barrage. Although this barrage can be flushed to free up space, it is not without consequences. A major flushing in 2019 released a high sediment load, causing environmental harm downstream in Kruger National Park. Sediments can also adsorb metals and toxins, lowering their concentration in the water. However, this process traps these contaminants in sediments, making them accessible to bottom-dwelling organisms. They also may be released back into the water through disturbance or changes in physical or chemical conditions [64].

The Ecological Water Requirement (EWR) specifies specific areas in the catchment where the water flow and quality levels are comprehensively studied to sustain the ecological health and functioning of river ecosystems within the Olifants catchment area. EWR nodes that lie in the B7 watershed were generally classified to be in mediocre ecological states, all had high ecological importance and half were deemed to be extremely sensitive to changes. Key water quality variables and their indicators were defined as follows [11]:

- **Electrical Conductivity (EC)** (mS/m): water salinization
- **Orthophosphate (PO_4-P)** (mg/L) and **Nitrate (NO_3+NO_2-N)** (mg/L): eutrophication levels
- **Sulphate (SO_4^{2-})** (mg/L): mining impacts
- **Chloride (Cl^-)** (mg/L): agricultural, sewage, and industrial
- **Ammonia (NH_3-N)** (mg/L): toxicity levels
- **pH**: mining impacts and natural variations

Figure 3.2 presents data from an EWR report table, illustrating the significant effects of effluent discharge and mining activities in the Phalaborwa area, which have markedly impacted water quality.



Monitoring Point	Cl-	EC	NH3-N	PO4-P	SO4 2-	pH	NO3+NO2-N
B7H002Q01 NGWABITSI RIVER AT TOURS	9.082	18.31	0.119	0.015	10.633	7.885	0.207
B7H004Q01 KLASERIE RIVER AT FLEUR DE LYS	11.737	13.48	0.114	0.02	12.145	7.954	0.24
B7H007Q01 AT OXFORD ON OLIFANTS RIVER	51.366	57.45	0.165	0.02	71.728	8.553	0.652
B7H010Q01 NGWABITSI RIVER AT HARMONY	12.8	24.8	0.121	0.016	10.164	8.102	0.135
B7H013Q01 MOHLAPITSE RIVER AT MAFEFES/HORN GATE	8.767	31.2	0.108	0.016	8.547	8.393	0.151
B7H014Q01 SELATI RIVER AT CALAIS	16.165	30.58	0.105	0.016	9.366	8.294	0.214
B7H015Q01 OLIFANTS RIVER AT MAMBA/KRUGER NATIONAL PARK	55.298	65.19	0.122	0.022	76.679	8.557	0.736
B7H017Q01 OLIFANTS RIVER AT BALULE REST CAMP/KRUGER NAT PAR	61.303	65.715	0.168	0.023	91.858	8.472	0.634
B7H019Q01 GA-SELATI RIVER AT LOOLE/FOSKOR	276.942	272.25	0.214	0.425	790.741	8.582	0.73

Figure 3.2: 2011 Water Quality Reports in the B7 watershed, showing the numbers of the 95th percentile [11], blue = IDEAL, green = ACCEPTABLE, yellow = Tolerable, red = UNACCEPTABLE

Groundwater quality is deteriorating due to various sources of contamination, including pit toilets, industrial and domestic waste, inappropriate cemetery locations, and both legal and illegal solid waste dumping. Additionally, developments lacking adequate septic tank systems further contribute to this issue [7] [48]. Groundwater quality in Phalaborwa was classified as class 2 'marginal' due to elevated sodium and chloride levels [79]. Throughout the region groundwater quality is generally good for non-potable use, but not potable use. The same applies to the Malmani Dolomites, which will likely require water treatment to soften the water, lower the total dissolved solids, lower anthropogenic nitrates, and treat microbial contamination [47].

3.1.5 Climate Change

Climate change poses a significant threat to the Olifants catchment, with projections indicating a rise in average temperatures by 1°C to 5°C and a potential reduction in precipitation of 2.5% to 58.7% under various representative concentration pathways (RCPs) [55]. This scenario is further exacerbated by increasing population and economic growth, intensifying pressure on the already stressed water resources of the Olifants. The combined impacts of climate change are expected to lead to declines in key crop yields ranging from 5% to 65%, while alterations in the hydrological cycle can exacerbate groundwater depletion and salinization, compromising water security in the region [53]. Furthermore, projections indicate that the pressure on water supply due to economic activities may lead to a significant increase in unmet water demand by 58% to 80% by the end of the century [56]. Therefore, implementing adaptive strategies, such as improved irrigation practices, rainwater harvesting, and a combination of effective management strategies, is crucial to mitigating the adverse effects of climate change on agricultural productivity and groundwater resources in the Olifants catchment.

3.1.6 International Obligations

As stated in the 2011 Olifants reconciliation plan [19], South Africa's obligations in the Olifants River Basin are shaped by historical agreements with Portugal, which governed Mozambique at the time, and South Africa's commitment to the Southern African Development Community (SADC). Under the 1971 agreement, South Africa and Portugal agreed on the raising of the Massingir Dam in Mozambique without compensation to South Africa, with the understanding that water flow in the Olifants river would decrease, and South Africa would refrain from using Massingir Dam water for any purposes other than domestic and livestock use. Additionally, earlier agreements grant South Africa flexibility to pursue further developments freely within its portion of the catchment area. However, under the SADC, South Africa is committed to sustainably managing shared watercourses in an equitable and reasonable manner, working to prevent negative impacts on neighboring countries. This protocol emphasizes cooperation through the exchange of information, but does not state minimum legal flow rates.

3.1.7 Water Demand in the Lower Olifants

2014 water balances report slight deficit in the western part of B7 and neutral levels in the east. Even though increases in water demand across all sectors have been discussed, recent data has not been found [64]. Older estimates, like the 2011 water balance for the Lower Olifants, as shown in figure 3.3 show even bigger surpluses.

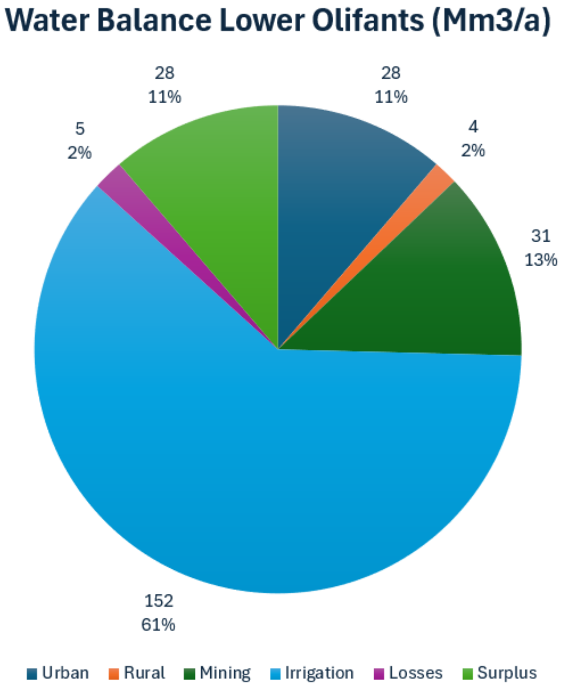


Figure 3.3: 2011 Lower Olifants water balance from DWS reconcilation strategy [9]

Nevertheless, irrigation in the Lower Olifants region is extensive, covering nearly 12,000 hectares within formal irrigation schemes and an additional 8,500 hectares of uncontrolled irrigation in the Ga-Selati River catchment. It is almost certain that uncontrolled irrigation and other water uses are unaccounted for in these balances. Rural water demands are primarily met by groundwater, except in the Ga-Selati River catchment, where water is transferred from the Thabina Dam in the neighboring Groot Letaba catchment. Mining operations around Phalaborwa rely on water from the Phalaborwa Barrage on the Olifants River, which is supplemented by releases from the Blyderivierpoort Dam and the Groot Letaba River [11]. The Phalaborwa Barrage currently has a maximum capacity of 150 Ml/day, of which 76 Ml/day is potable. Reports from 2011 indicate that daily consumption is at 131 Ml/day [7], and it is likely that the demand is greater due to regions without meters and illegal tapping. During a conversation with PMC, they reported that approximately 20 Ml/day is delivered by the Barrage. However, their requirements of 120 Ml/day are much greater. Most of the water is recycled in PMC's closed water circuit [13]. Unsurprisingly, the true water demand in the Lower Olifants region or Phalaborwa, remains unknown. As a result, all available water balances are only partially useful due to data gaps.

3.2 Experimental Study 1: Creation and Assessment of a Simple Water Balance for B72D

3.2.1 Context and Significance of a Water Balance

The Phalaborwa region in Limpopo faces significant water management challenges due to its semi-arid climate, high evaporation rates, and competing demands from mining, agriculture, and local communities. Developing a water balance is crucial for understanding the availability and distribution of water resources in this context. Given the region's unpredictable rainfall and frequent droughts, a water balance helps quantify the inflows, outflows, and storage of water, enabling better planning and management during periods of scarcity. With large-scale mining and irrigation-based agriculture being major water consumers, the balance enables decision making to make these activities more sustainable without depleting future resources or harming the environment.

A water balance (Figure 3.4) describes water availability and demand, based on flow coming in and out of a catchment area. Water enters a catchment area through precipitation, runoff, and groundwater inflow, while it exits via evapotranspiration, river flow, and various domestic and industrial uses. The annual water balance assesses the availability of water in relation to its demand, helping to identify sub-catchments that are experiencing water surplus, equilibrium, or deficit. The goal of this section is to develop detailed biophysical maps for the B7 catchment area as part of a simplified water balance approach. These maps will enhance our understanding of the watershed's functioning, even in the absence of full data for a detailed water balance calculation. Gauge data was retrieved from the National Hydrology Database [69], and maps not originally created for this report were sourced from WR2012 [68]. Additional maps not included in the report can be found in Appendix A. The raw VisualCrossing dataset is available upon request.

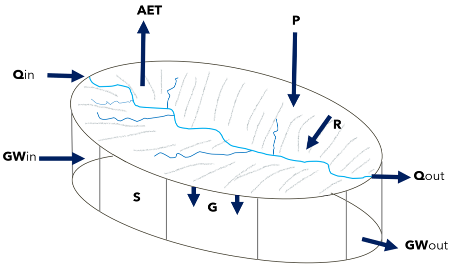


Figure 3.4: Schematic diagram of a watershed, with components of a simple water balance: P = precipitation, AET = actual evapotranspiration, Q = river discharge, GW = groundwater flow, G = groundwater recharge, R = surface water runoff, S = storage

3.2.2 Study Area

Figure 3.1 shows the B7 catchment, where one can also see the Digital Elevation Model (DEM) of pixel size 30x30 (m) used throughout this study obtained from the COP-30 [28]. Also, the registered primary and secondary rivers are displayed, alongside the delineated drainage paths which were acquired during the process of watershed delineation in ArcGIS Pro with the ArcHydro Plugin. Furthermore, the B7 region contains a multitude of river and meteorological stations. Unfortunately, many tributary catchment points have incomplete monitoring records, resulting in data gaps. The study area for the water balance encompasses the B72D quaternary catchment, as shown in figure 3.5, which is a sub-catchment of the B7 watershed. As illustrated in figure 3.5, the watersheds included in the water balance slightly extend beyond the B72D area due to the locations of river gauges. This approach ensures that the balance accounts for all contributing drainage areas. Just like the drainage paths in figure 3.1, the watersheds in question were delineated using the ArcHydro Plugin based on the topography obtained from the DEM.

3.2.3 Methodology

Water Balance Equation

For this study of the B72D catchment, the surface water balance is described as follows:

$$\Delta S = P - ((AET + R + Q_{out}) + G + Q_{in}) \tag{3.1}$$

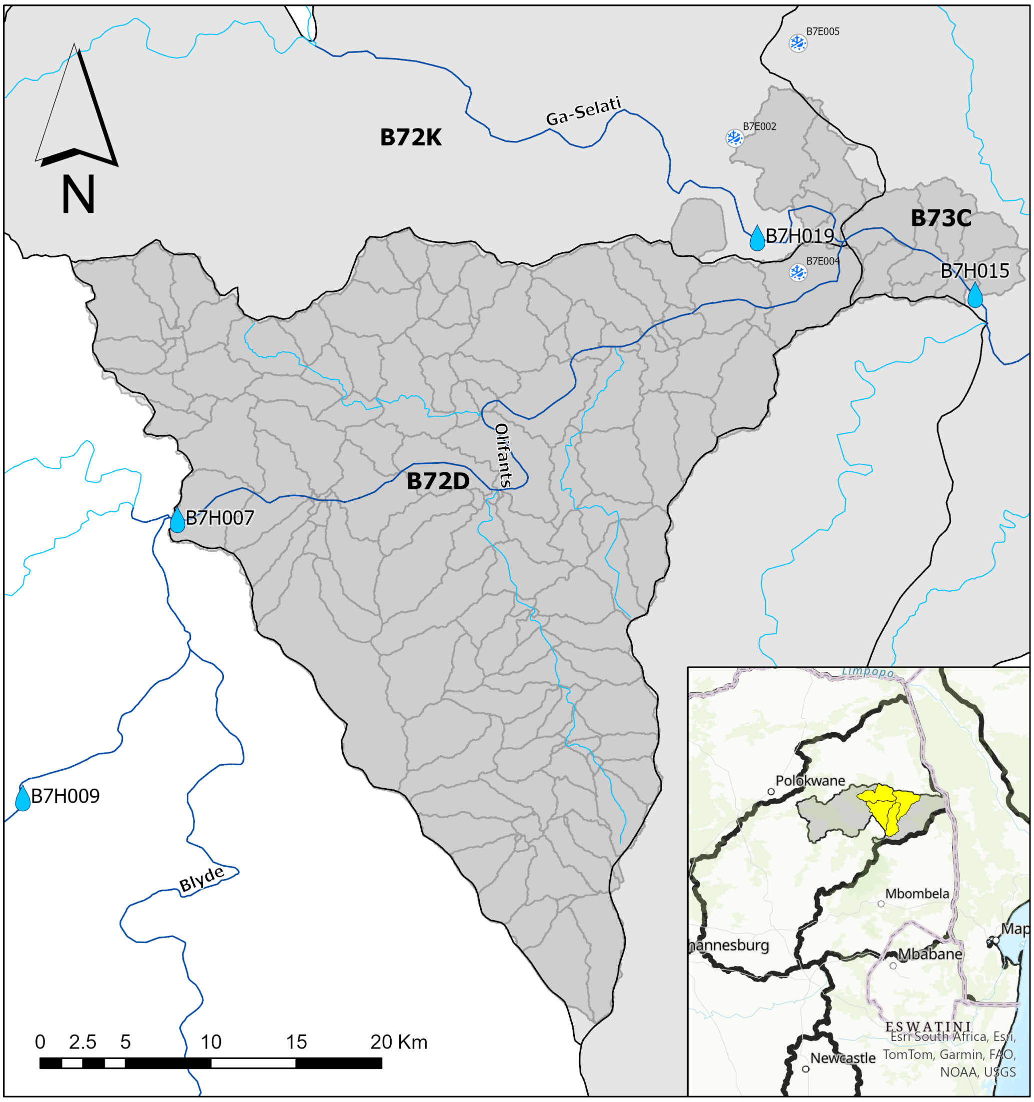


Figure 3.5: Study area B72D quaternary catchment and delineated sub catchments (dark grey)

Where ΔS represents the change in water storage within the watershed, AET is the actual evapotranspiration, R is the runoff, Q represents the river flow and G is the groundwater recharge. This equation serves as the foundation for assessing water dynamics in the catchment area. It is important to note that the complexity introduced by the Phalaborwa Barrage, for which recent dam records are unavailable, may influence the accuracy of our estimates. Additionally, subsurface flow is assumed to be negligible in this analysis due to the lack of hard data. Other fluxes, such as irrigation, have also been neglected to simplify the balance. Therefore, careful consideration was given when interpreting the results of this water balance assessment.

Precipitation

Annual average precipitation data were obtained from the VisualCrossing dataset for Phalaborwa, covering the years 2006 to 2024. For simplicity, it was assumed that precipitation is constant throughout the studied watershed. Monthly spatially variable maps were created by updating the relatively outdated WR2012 precipitation maps, using the mean precipitation data from Phalaborwa to scale the entire grid accordingly. It is important to note that the adjustment of rainfall across the entire B7 watershed was based on a single rainfall station in Phalaborwa. While it is assumed that this method will not introduce significant issues within the Lowveld region, caution should be exercised when interpreting precipitation values in the escarpment and areas west of the escarpment due to the introduction of potential bias.

Evapotranspiration

In this study, the Turc method was chosen to estimate potential evapotranspiration (PET) for the B7 catchment in South Africa. The Turc method is well-suited to semi-arid and sub-tropical climates, where it effectively captures PET dynamics with limited data requirements [73]. This method uses monthly mean temperature and solar radiation to estimate PET, providing an approach in areas where relative humidity (RH) generally exceeds 50%, as is typical in the Lowveld region during much of the year. Given that RH levels above 50% reduce the variability in PET due to humidity, the unadjusted Turc method was applied, as its original formulation assumes ample atmospheric moisture. The equation used is a follows:

$$PET = \frac{0.0133 \cdot (T_m + 15) \cdot (R_s + 50)}{T_m + 15} \tag{3.2}$$

where PET is the potential evapotranspiration, T_m is the mean monthly air temperature in degrees Celsius (°C), and R_s is the mean monthly solar radiation in calories per square centimeter per day (cal/cm^2/day). To assess the relative humidity (RH) and temperature values, the VisualCrossing dataset was consulted, which can be found in Appendix A. It was determined that RH values consistently exceeded 50% throughout the year. Additionally, temperature maps were obtained from the WR2012 dataset and adjusted to reflect the new mean temperature, following the same methodology used for updating precipitation data described in the previous section. The monthly solar radiation was obtained using the Area Solar Radiation tool in ArcGIS Pro, which utilizes a DEM as input. The modeling options include the use of the "standard sky model", which accounts for both direct and diffuse solar radiation. A diffuse proportion of 0.3 was selected to reflect the typically clear skies in the region. Additionally, transmittivity was set to 0.6. The irradiance maps generated were compared to the SolarGIS open-access data and were found to be of the same order of magnitude, with the ArcGIS-generated maps providing higher detail due to the high pixel density of the DEM. The calculated PET had to be adjusted to reflect Actual Evapotranspiration (AET), as PET represents the maximum amount of water that could be evaporated and transpired under optimal conditions. In reality, there are times when water is unavailable, leading to AET values that are generally much lower than the PET. To adjust the PET values, the data was scaled based on AET estimates from the United Nations FAO [1]. However, it was not possible to rely solely on the FAO data because it only includes very recent years, which do not correspond with the river flow data used in this study. For the calculation of the water balance, a single median AET value for B72D was considered.

Runoff, Recharge, Baseflow and Available Water Capacity

The value for recharge (6.4 mm/year) and baseflow (0 mm/year) used in this study were sourced from the WR2012 study. Runoff was calculated by multiplying precipitation with the runoff coefficient obtained from a previous hydrologic study, that estimated the runoff coefficient to be 0.06 for the B7 catchment [51]. Runoff refers to the portion of precipitation that flows over the land surface and enters rivers and streams, contributing to surface water bodies. The value of 31.63 mm/year indicates a relatively low level of surface runoff, which may be characteristic of the region's semi-arid climate and vegetation cover. Recharge represents the amount of water that infiltrates into the soil and replenishes groundwater supplies; in this case, 6.4 mm/year suggests a modest level of groundwater replenishment. Baseflow, defined as the sustained flow of water in a river or stream that comes from groundwater discharging into the surface water, is indicated to be 0 mm/year in this study. This suggests that there is no significant contribution from groundwater to the river flow. Available Water Capacity (AWC) was initially determined for the water balance calculations but ultimately was not used due to the unnecessary complexity it introduced into the balance. However, given that AWC provides significant benefits from an agricultural perspective, the maps and calculations are included in the report and can be found in Appendix A.

River Flow

Three gauges are considered in this balance, namely: B7H007 (inlet), B7H019 (Ga-Selati outlet), B7H015 (outlet). To gain an understanding of the balance over a longer period of time, the flow records from 2005 until 2021 are considered. The data is not complete as can be observed in table 3.3. Records that were flagged by the gauges were substituted by the median values of the other monthly flow records of the particular river gauge, meaning that a substantial portion of primarily the B7H007 record was substituted with estimate values. The median is used to measure central tendency, since the mean is more sensitive to extremes such as during a flood or drought event. Therefore, also the values incerted into the balance are the median values of the inlet and outlet.

Table 3.3: Data gaps of gauges B7H007, B7H019, and B7H015

Description	**B7H007**	**B7H019**	**B7H015**
Total Records	192	192	192
Incomplete Records	45	13	8
Above Rating	15	1	0
Estimates	3	4	0

3.2.4 Results & Discussion

Applying the water balance equation to the data reveals an annual balance as presented in Table 3.4. Except in spring, when the first major rainfall occurs before temperatures reach their peak, the watershed shows a significant and consistent water deficit throughout the year based on the employed methodology. Furthermore, the analysis shows that annual precipitation is considerably lower than AET, suggesting that most, if not all, inflows resulting from precipitation are effectively lost to evapotranspiration. In reality, it is evident that rainfall occurs with high intensity, which is capable of recharging groundwater and generating runoff that could exceed the reported values. This discrepancy between observed runoff and the potential runoff indicates that there may be factors at play that are not fully captured by the current water balance calculations. High-intensity rainfall events, while contributing to immediate runoff, may also result in rapid infiltration and subsequent groundwater recharge that is not reflected in surface water measurements. Reports indicate that runoff is very close to zero during the dry months but can exceed 500 mm during the wet season [22]. The flow data measured at the gauging stations, illustrated in figure 3.6, demonstrates clear annual variations in river flows, heavily influenced by periods of intense precipitation or extreme drought. Notably, the hydrological year of 2015/2016 experienced severe drought conditions, which is evidenced by inflow surpassing outflow. This anomaly can likely be attributed to increased water abstraction at the Phalaborwa Barrage, implemented to alleviate water stress in the surrounding community. The observed and sustained deficit of several hundreds of million cubic meters within the watershed raises important questions about water management practices in the region. While the methodology provides a straightforward framework for understanding water dynamics within the B72D watershed, it does not fully address the complexities inherent in the hydrological system. Factors such as the ability of the soil to store moisture, anthropogenic influences including the Phalaborwa Barrage, its wastewater treatment works, irrigation and the industry located in the PIC have been overlooked.

Despite the simplicity of the model, the data from 2005 to 2021 underscores the need for a holistic and updated approach to water management in the B72D watershed, as well as in other watersheds within the B7 region. This necessity is particularly evident given that most other quaternary catchments lack inlet and outlet gauging stations, resulting in limited detailed water balances. This study suggests that current water usage may exceed the sustainable yield of the watershed, though this conclusion comes with significant uncertainty due to the model's inherent limitations. Future research should prioritize enhancing the accuracy of water balance components through improved data collection, monitoring techniques, and uncertainty/sensitivity assessments. Investigating the role of groundwater is highly recommended, as it is unlikely that groundwater systems do not influence surface water dynamics. Additionally, further examination of the effects of land use changes and climate variability (specifically drought and flood events) will provide valuable insights into the hydrological behavior of the region.

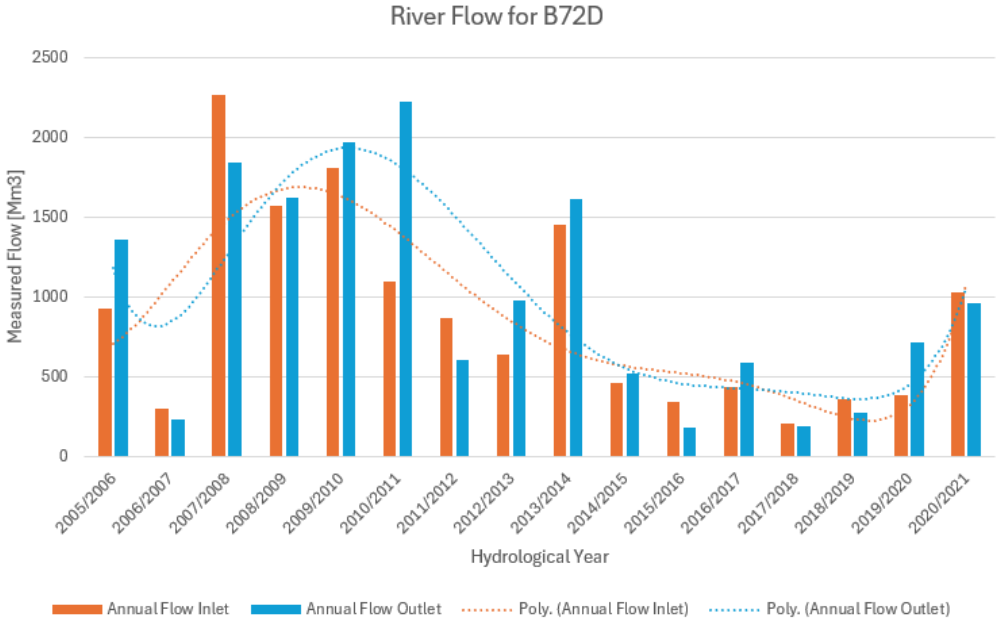


Figure 3.6: River flow for watershed B72D, where the inlet shows the annual flows of B7H007 and the outlet shows the annual flow of (B7H015-B7H019)

Table 3.4: Monthly Water Balance for the B72D Catchment

Month	P **(mm)**	Q_{in} **(Mm^3)**	Q_{out} **(Mm^3)**	PET **(mm)**	AET **(mm)**	AET/PET **(%)**	R **(mm)**	G **(mm)**	ΔS **(Mm^3)**
Oct	38.46	13.85	11.38	232.00	34.41	15%	2.31	0.53	4.79
Nov	71.38	22.20	27.21	253.00	45.83	18%	4.28	0.53	17.26
Dec	93.09	37.10	61.85	260.00	64.17	25%	5.59	0.53	-0.37
Jan	96.77	83.85	129.87	257.00	89.77	35%	5.81	0.53	-44.26
Feb	88.94	86.40	165.58	243.00	86.28	36%	5.34	0.53	-81.37
Mar	61.19	66.00	95.54	208.00	89.58	43%	3.67	0.53	-61.74
Apr	34.47	37.70	51.80	172.00	61.65	36%	2.07	0.53	-43.43
May	11.67	45.70	40.84	135.00	49.32	37%	0.70	0.53	-33.76
Jun	5.25	23.90	22.18	113.00	30.81	27%	0.31	0.53	-24.17
Jul	5.73	20.20	15.96	128.00	30.14	24%	0.34	0.53	-20.50
Aug	4.81	16.60	13.97	155.00	30.00	19%	0.29	0.53	-22.84
Sep	15.47	10.21	7.49	197.00	27.97	14%	0.93	0.53	-10.45
Annual	527.24	753.08	838.38	2353.00	639.93	27%	31.63	6.40	-226.19

3.2.5 Conclusion

This study analyzed the water balance for the B72D catchment due to its access to strategic river gauges, revealing a significant annual deficit due to annual precipitation being considerably lower than actual evapotranspiration (AET). High-intensity rainfall events may recharge groundwater more and generate more runoff, but these processes are not fully captured in current calculations. Given that water usage likely exceeds the watershed's sustainable yield, there is a pressing need for improved water management practices. Future research should enhance data collection on groundwater dynamics and examine the effects of land use changes and climate variability to ensure long-term sustainability of water resources in the entire B7 catchment. Efficient water-use among the community should be encouraged to minimize the stress on the watershed.

3.3 Experimental Study 2: Potential for Rainwater Harvesting in Phalaborwa Town

3.3.1 Introduction

Increasing pressure from the ever-growing demand for water forces communities experiencing scarcity to adapt. Rainwater collection for non-potable or irrigation uses is not a new innovation in urban areas, but it is a highly effective one [4]. This potential has not gone unnoticed; some cities around the world now require new building plans to include rainwater harvesting systems for approval [36].

Rainwater harvesting not only has the potential to lower demand on the water grid and create more water security, but it also reduces stress on groundwater abstraction and minimizes stormwater runoff. Additionally, it helps decrease erosion and non-point source pollution in urban areas. Rainwater harvesting collects naturally soft water that is suitable for non-potable indoor uses, and with proper treatment, it can be made safe for drinking. Besides yielding significant amounts of water, rainwater harvesting offers decentralized water collection, which can be more cost-effective compared to alternatives like well drilling or municipal water supplies. It also helps reduce water losses and enhances supply in watershed systems [66].

Moreover, using rainwater harvesting and other simple technologies can lower greenhouse gas emissions associated with water storage and treatment, contributing to climate change mitigation [4]. Current water consumption values are difficult to ascertain, and much of the available open-source data is outdated by at least a decade. Additionally, sources tend to provide conflicting estimates. The Mopani District reports a consumption of 964 l/p/d at 104.65% of available capacity for the Phalaborwa Municipality [49]. Other sources indicate that within the municipality, 22% of households have zero consumption, and the town of Phalaborwa consumes 65 kl/household/month [5]. Whereas, the DWS reports 194 l/p/d in Olifants River System in 2022 [54]. These conflicting values are unsurprising, as reports indicate that only 39% of consumers are metered and billed, while the remaining 61% receive water at no cost, which has significant consequences for the municipality [5]. Furthermore, these varying values may reflect different measurement methodologies, such as the inclusion of industrial water demands in the assessment.

3.3.2 Methodology

Study Area

Phalaborwa Town was specifically taken for the study on rainwater harvesting potential, primarily due to computational restrictions of the rooftop classification. The extent of the study area can be found in figure 3.9.

Determining Demand

To estimate the water consumption of the local households, it was necessary to know both the total population and their respective consumption. Detailed population reports are outdated; the current population of the municipality is taken to be 188,603, with an average household size of 3.7 [48]. The population of Phalaborwa town was previously reported to be 13,052, back when the municipal population was reported to be 150,637 [2]. For this research, it was assumed that the growth within the municipality was uniform at 25.2% and Phalaborwa town could be scaled accordingly. Therefore, the 2022 estimate for Phalaborwa town was calculated to be 16,341. Consumption was assumed to be equivalent to the previously mentioned DWS statistic of 194 l/p/d, which translates to ± 97 Ml/month. The decision was made based on its alignment with global water use, around 100 l/p/d, ensuring consistency with internationally recognized domestic consumption patterns. Furthermore, it was assumed that the demand is consistent throughout the year.

Rooftop Areas

To determine the rooftop area available for harvesting rainwater, two methods were implemented using ArcGIS Pro. The first method involved supervised classification utilizing high-resolution aerial photographs [10], while the second method employed AI-based classification provided by Google Open Buildings.

For supervised classification, training samples were manually digitized within ArcGIS Pro. Representative samples for each land cover type (e.g., rooftops, vegetation, roads, and bare ground) were identified and manually digitized to create a comprehensive training dataset. Specifically, polygons were drawn over known rooftops to capture a range of rooftop materials, shapes, and sizes, ensuring a robust representation across the study area. A total of 60 polygons were utilized to train the classifier. The Support Vector Machine classifier was chosen due to its ability to handle complex classes and spectral variation within the imagery. Using the digitized training

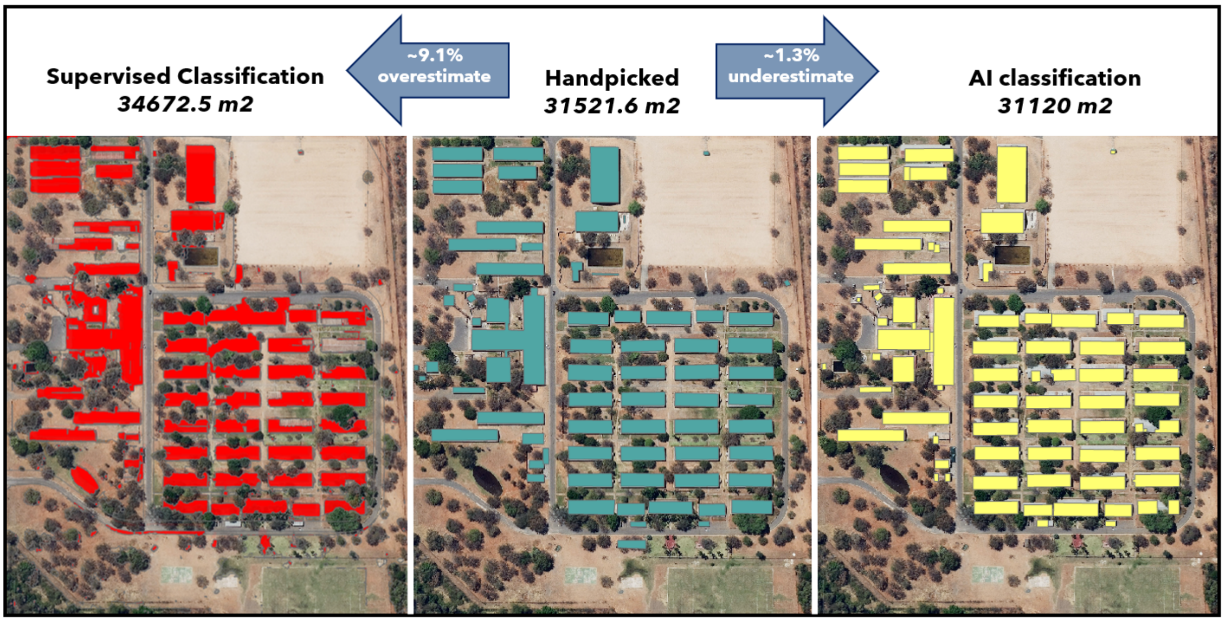


Figure 3.7: Part of Phalaborwa Army Base that was used to study the accuracy of the rooftop classifiers

samples, the classifier was trained to recognize rooftops based on their spectral and spatial characteristics as derived from the aerial imagery. Once the model was trained, it was applied to the entire dataset, producing a classified raster where each pixel was assigned to a specific land cover class.

To assess the quality of the automated classification methods, the author handpicked rooftops from a portion of the Phalaborwa army base, as the barracks have a predictable rectangular shape. This predictability allowed for reasonable assumptions about the existence of rooftops, even when trees obstructed the view. The two method's output areas of the rooftop were compared to the handpicked ones to determine accuracy, as observed in figure 3.7.

The results of the quality assessment indicated that the AI-based classification tool outperformed the supervised classification method in accurately delineating rooftop areas, with an underestimation of 1.3% compared to a 9.1% overestimation by the supervised classifier. While the AI classifier required significantly greater computational resources, it demonstrated a superior capability to identify rooftops even when obstructed by non-rooftop pixels. In contrast, the supervised classifier exhibited a tendency to misclassify pixels that shared similar spectral characteristics with rooftops, resulting in notable inaccuracies in the classification output. As a result, the rooftop area value from the AI classifier, adjusted for a 1.3% underestimation, was utilized for the final estimation.

Precipitation

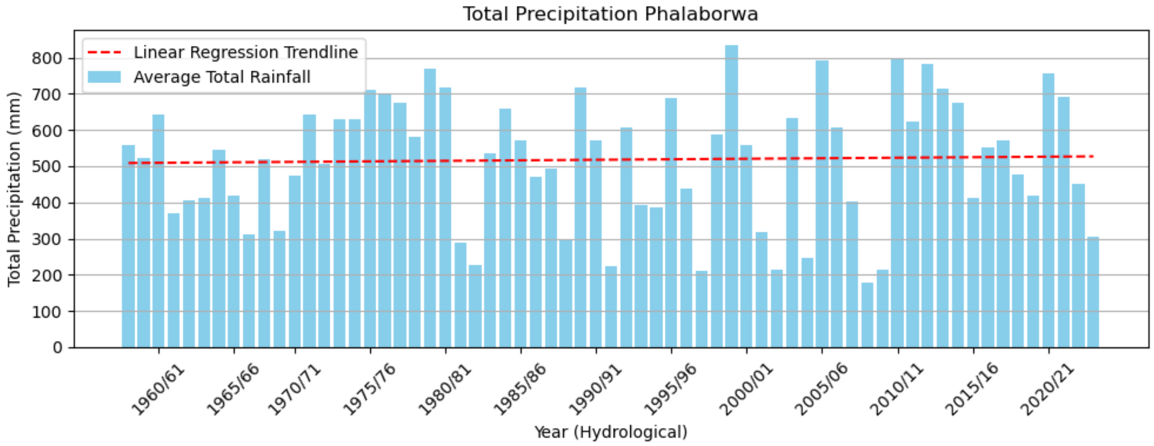
Local precipitation data is available from 1958 to 2024, sourced from a combination of four different measuring stations, as shown in Table 3.5. The B7 meteorological stations are state-owned and open source, while the VisualCrossing dataset is proprietary. The latter was included to ensure the data is up to date.

Table 3.5: Precipitation Data Origin

Station Name	**Data Availability**	**Ownership**	**Coordinates (°)**
B7E002	1958-1965	Government	(31.11645, -23.98402)
B7E004	1967-2006	Government	(31.14979, -24.05485)
B7E005	1967-1980	Government	(31.14979, -23.93403)
VisualCrossing	2006-2024	Private	(31.15000, -23.93300)

Figure 3.8 illustrates both total annual and average monthly precipitation in Phalaborwa. It is important to note that the government datasets include four years with gaps in the data (1957/58, 1966/67, 1967/68, 1975/76); however, these gaps were deemed small enough to be ignored. From Figure 3.8, it is evident that total annual precipitation is relatively stable at 518 mm/year, slightly above the 463 mm/year forecast for the

Lowveld area available on various weather websites. Variability in the datasets was assessed by calculating the coefficient of variation, defined as the standard deviation divided by the mean. Results indicated moderate (0.33) variability in annual precipitation, but very high (1.13) variability in monthly rainfall. This suggests unpredictable rainfall patterns on a monthly basis.



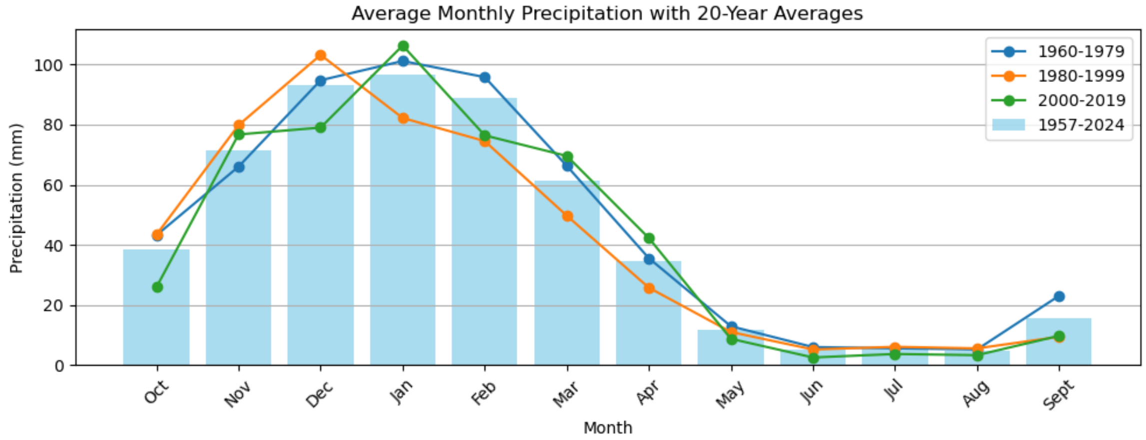


Figure 3.8: Rainfall data of Phalaborwa based on measurements from 4 stations listed in 3.5

3.3.3 Harvest Potential

The amount of rainwater that can be harvested is influenced by the roof area, rainfall depth, the storage volume and runoff coefficient, which is affected by the roof's material and design [72]. The formula for calculating rainwater harvesting was given by the following equation adapted from [4]:

$$RH = \frac{P \cdot A \cdot R_c}{1000} \tag{3.3}$$

where RH is the harvested precipitation (m^3), P is the precipitation (mm), A is the rooftop area (m^2), and R_c is the runoff coefficient $(dimensionless)$. The harvest potential was assessed for every month of the year, and subsequently compared to the estimated demand to generate a balance. For the runoff coefficient value an estimate of 0.70 was used, equivalent to the runoff of a concrete roof, which is considered to be low compared to other materials [42]. This value accounts for losses in runoff and evaporation.

3.3.4 Results & Discussion

The analysis of rainwater harvesting potential in Phalaborwa Town reveals both opportunities and challenges in addressing the community's water scarcity issues. The data reveals significant variability in precipitation, impacting the overall effectiveness of rainwater harvesting systems. Nevertheless, the data shows stable trends throughout the studied period. From October to February, rainfall is relatively high, peaking in January with 97 mm, leading to substantial harvesting volumes. For example, in December, the estimated harvested volume reaches 100,319 $\mathbf{m^3}$, which exceeds the calculated demand of 96,690 $\mathbf{m^3}$, yielding a positive balance of 3,629 $\mathbf{m^3}$. This suggests that during wetter months, the potential for rainwater harvesting can not only meet the local demand but also provide surplus water for storage or supplementary use. Conversely, the dry months from May to August demonstrate a stark contrast in available harvested volumes, with values plummeting to as low as 5,655 $\mathbf{m^3}$ in June. The significant shortfall in these months, particularly in May (-84,114 $\mathbf{m^3}$) and June (-91,034 $\mathbf{m^3}$)—indicates that reliance solely on rainwater harvesting during this period would be inadequate to meet community needs. Nevertheless, storage capacity remains a critical concern for rainwater harvesting systems. If each household of 3.7 individuals were equipped with a 5 $\mathbf{m^3}$ JoJo tank, it would only store about 22.8% of the Phalaborwa's estimated monthly domestic water demand. This storage would enable effective utilization of harvested rainwater during wetter months, provided rainfall is relatively uniform. In reality, intense downpours and flash floods occur, leading to significant runoff and losses. Thus, optimizing rainwater harvesting in Phalaborwa requires enhancing storage capacities and improving management strategies for extreme weather events to maximize water capture. Additionally, the coefficients of variation show that full reliance on rainwater can be a dangerous undertaking due to unpredictable rainfall patterns.

As indicated, demand figures remain uncertain, primarily due to discrepancies in reported consumption values and the limited number of metered consumers. The assumption of a consistent 194 l/p/d across the year, while aligned with global standards, may not fully capture local dynamics. Furthermore, this study does not look into potable water requirements, or the applicability of rainwater for domestic water use. Engaging with local households to gather more accurate water use data could refine demand estimates, numbers on rainwater utilisation and lead to more effective rainwater harvesting strategies. The surface area of roofs in this study was assumed to be utilized at 100%. However, in practice, connecting all classified roofs to a collection system would be highly challenging. Nonetheless, it is assumed that the decision to adopt a conservative runoff coefficient partially compensates for this limitation. Also, numbers on already installed rainwater harvesting systems are not incorporated in this study, making the impact on current water consumption likely lower than shown in table 3.6.

The integration of rainwater harvesting systems aligns with broader sustainability goals, particularly in reducing greenhouse gas emissions related to water sourcing and treatment. By minimizing the reliance on municipal water supplies, which often involve extensive energy use in treatment and distribution, communities can move toward more sustainable practices. The decrease in stormwater runoff further contributes to urban environmental management by lessening pollution loads on local water bodies due to reduction of sewage overloads.

Table 3.6: Monthly Rainwater Harvest Potential

Month	**Monthly Precip (mm)**	**Harvest Volume ($\mathbf{m^3}$)**	**Demand (DWS) ($\mathbf{m^3}$)**	**Balance ($\mathbf{m^3}$)**	**Percentage Potential Supply From Rainwater**
Oct	38	41444	96690	-55246	43%
Nov	71	76918	96690	-19771	80%
Dec	93	100319	96690	3629	104%
Jan	97	104279	96690	7589	108%
Feb	89	95841	96690	-848	99%
Mar	61	65942	96690	-30748	68%
Apr	34	37147	96690	-59543	38%
May	12	12576	96690	-84114	13%
Jun	5	5655	96690	-91034	6%
Jul	6	6175	96690	-90515	6%
Aug	5	5188	96690	-91501	5%
Sept	15	16675	96690	-80015	17%

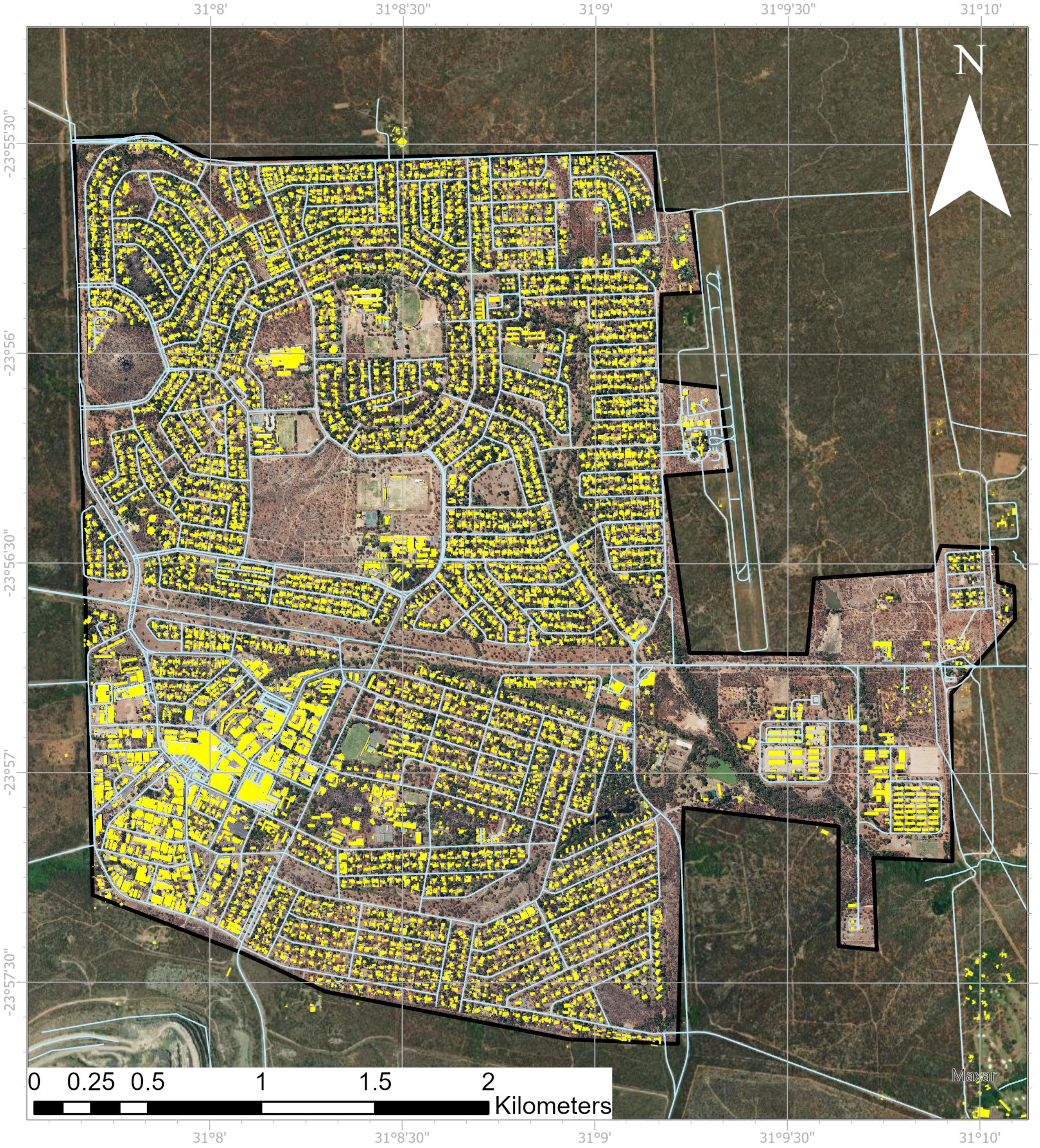


Figure 3.9: Study Area (black border) showing rooftops classified by the Google Open Buildings AI (yellow)

3.3.5 Conclusion

In conclusion, while rainwater harvesting presents a viable option for enhancing water security in Phalaborwa, significant challenges remain. Monthly rainfall variability necessitates comprehensive storage solutions, and discrepancies in water consumption data underscore the need for more localized assessments. Additionally, reliance on this method is complicated by the potential for droughts that can affect the region. Therefore, further feasibility studies are advised to explore strategies for optimizing rainwater harvesting and improving resilience against water scarcity.

3.4 Water Saving Strategies

3.4.1 Centralized Water Solutions

A centralized water data hub tailored to Phalaborwa could provide local authorities with real-time information on water levels, usage rates, and resource distribution across sectors. This platform would enable more dynamic water management, allowing for quick responses to trends such as unexpected demand spikes or declining groundwater levels. By investing in digital technologies, including IoT sensors and satellite imagery, Phalaborwa could monitor water usage across farms, households, and industrial sites, enforcing more responsive, targeted water-saving measures and attracting high-skilled labor to the region. An additional strategy is enhancing metered infrastructure to provide a comprehensive view of consumption patterns. With precise data on water use, authorities can encourage best practices, such as drip irrigation for crops in arid regions. Furthermore, as noted earlier in the chapter, halting uncontrolled borehole drilling would help water management authorities gain a clearer picture of regional water stress, facilitating more effective conservation. Finally, water-use efficiency can be improved through innovative building designs that maximize rainwater capture. Roofs optimized for rain collection and Venetian-style cisterns could significantly boost rainwater harvesting, providing a sustainable source of grey water for households and reducing strain on local resources.

3.4.2 Artificial Recharge

Artificial recharge replenishes groundwater by channeling surplus surface water or treated wastewater into aquifers, helping stabilize reserves in regions with seasonal shortages or over-extraction. The feasibility of recharge depends on available storage space and aquifer permeability. In places like Dendron, SA, aquifers with declining levels due to overuse offer storage capacity, while high-permeability aquifers, such as those in Atlantis, SA, support infiltration of treated wastewater through borehole injection and basins [15]. Confined aquifers can also store injected water, forming fresh water compartments within saline aquifers, as is done in the USA [46].

Artificial recharge proves to be a sustainable strategy for enhancing water resilience, particularly with sources like treated wastewater, which provides reliable, year-round recharge. However, challenges arise in semi-arid regions, such as Phalaborwa. Here surface water is scarce, costs are high, and hard rock aquifers have likely limited storage capacity. Runoff is often insufficient and can disrupt downstream water availability, while direct recharge via dug wells risks contamination from agricultural runoff. In such cases, directing surplus basin water for seasonal irrigation can support groundwater indirectly through natural return flows. Promoting high water-use-efficiency crops and pricing irrigation water to reflect scarcity are essential for maximizing benefits and minimizing costs [40].

3.4.3 Removal of Alien Vegetation

The removal of invasive alien vegetation is another highly effective water-saving strategy, especially relevant to Phalaborwa and similar regions facing water scarcity. Alien plant species, such as certain acacias and eucalyptus trees, consume significantly more water than native vegetation, depleting groundwater and reducing surface water availability. By systematically clearing these invasive species, the region can restore natural water flows, increase groundwater recharge, and support biodiversity. Removing alien vegetation not only frees up water resources but also improves soil health and reduces fire risks, creating a healthier and more resilient ecosystem overall. This approach, combined with replanting indigenous species, can greatly contribute to sustainable water management in Phalaborwa. The value in the removal of alien vegetation has already been stressed by both governmental reports [19] and NGO's like Kruger 2 Canyons who actively work on their removal [39].

3.4.4 Efficient Agricultural Practices

Efficient agricultural practices present another pathway for water conservation, especially for a semi-arid region like Phalaborwa, where irrigation demands are high. Implementing drip irrigation can significantly reduce water use compared to traditional methods, as it directs water directly to plant roots, minimizing losses from evaporation and runoff. This method has shown success in similar climates, demonstrating its suitability for conserving water in local agricultural activities. Additionally, promoting drought-resistant crops can help align agricultural needs with limited water availability. Selecting crop varieties suited to low-water environments ensures that farming remains viable while reducing the burden on the region's water resources. These techniques, together, could help stabilize agricultural output and improve resilience to drought conditions.

3.4.5 Community Awareness and Incentives

Raising community awareness is essential for sustainable water management. Educational programs in schools and community centers could emphasize the importance of water conservation, equipping residents with actionable strategies for saving water at home, such as fixing leaks and using water-efficient appliances. Incentives for adopting these practices, like funding for water-saving fixtures or rainwater tanks could encourage greater participation. Local workshops could further support this initiative, offering practical guidance on how households can reduce water waste. Combined, these efforts can foster greater commitment to conservation, reducing overall demand and helping to preserve the region's water resources for the future.

3.5 WEF Nexus integration of Water

The understanding of the water resources, quality and saving strategies outlined in this chapter are central to reinforcing the WEF-nexus in the Phalaborwa region. Beyond implementing efficient water-saving techniques, there is a need to make strategic use of available water resources, like the Malmani dolomites, and to prioritize improved waste management practices to protect these water sources and ensure sustainable access.

The Malmani dolomites aquifer, with its capacity to provide a steady groundwater supply, could significantly reduce the region's dependence on surface water or limit the use of Lowveld groundwater. Responsible and sustainable development of this aquifer can support agriculture and local water needs, helping to stabilize water availability without degrading the aquifer over time. Drawing from groundwater reduces the energy costs associated with long-distance water transport, thus benefiting both the water and energy dimensions of the WEF-Nexus. In parallel, there is an urgent need to improve waste management practices to protect water quality. Shifting from pit toilets to centralized waste collection and improved sanitation facilities would mitigate the risk of groundwater contamination, preserving the quality of both surface and subsurface water. Effective waste disposal is essential to maintain water quality, supporting agricultural use and safe drinking water while reducing the need for energy-intensive water treatment. Improved sanitation infrastructure also protects community health and reduces vulnerability to waterborne diseases, directly supporting the broader goals of water security. Together, these water strategies, like effective use of groundwater reserves, centralized data hubs with ample data resources, potential artificial recharge, alien vegetation management, rainwater harvesting, improved waste practices, efficient farming practices and community-engagement are all critical to Phalaborwa's sustainable development within the WEF-Nexus context. By aligning water use with responsible management of water and waste, Phalaborwa can alleviate pressure on its water systems while bolstering energy and food security.

Chapter 4

Energy

4.1 Current Situation and Challenges

In Phalaborwa, residents face significant electricity challenges due to frequent power outages caused by aging infrastructure and lack of maintenance. The poor are mostly affected by these issues, often relying on illegal electricity connections and adapters, which not only pose safety risks but also overload the system. Corruption makes the situation worse, with frequent reports of stolen cables and transformers. Eskom, the primary electricity supplier, struggles to meet demand and maintain the grid, leading to greater outages and delayed fault repairs. This situation highlights the urgent need for infrastructure upgrades and better governance to ensure reliable electricity supply.

Currently, many communities rely on wood for cooking, as electricity is rarely used for this purpose. Often these houses don't even have a connection the the grid. Households lack running water, often using water from illegal boreholes and using buckets of water to flush toilets. Without electric lights, they resort to using candles. There are often no systems in place to catch rainwater in a proper way meaning that when there is natural water it is not being used to its full capacity. There is no public transport, forcing residents to walk long distances. The available electricity operates on a prepaid system, where users purchase a certain amount of electricity credit. The following mentioned situations have severe impacts: illegal power usage, infrastructure destruction, cutting of pipelines, no maintenance, lack of skills, and projects controlled by traditional authorities who are ill-equipped to address the major problems. Corruption, illegal installations, and grid overloading worsen the already terrible situation, leading to significant challenges for the residents of Phalaborwa. An example of what is happening in the whole of South Africa that can alarm us as westerns is to go against these illegal action is that the street lights are kept on so there is less theft, even during the middle of the day in bright summer.

In Fig 4.1 the statistics for the households in Phalaborwa are given and what is clearly visible is that there is no use of any kind of renewable energy. The electricity in blue is coal based and the fact that candles and wood is even taken into consideration shows how primitive the situation in this region is.

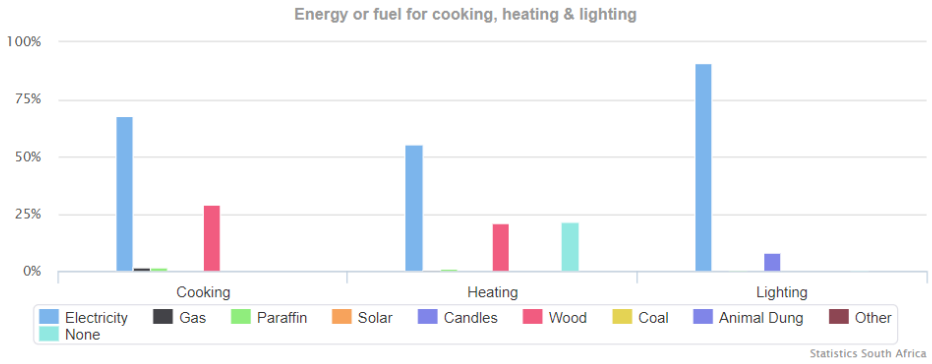


Figure 4.1: Source of energy used in Phalaborwa [71].

Eskom, South Africa's primary electricity supplier, plays a crucial role in the country's energy landscape. With a net maximum electricity generation capacity of 41194 MW. Eskom's power generation is predominantly coal-based, accounting for 85% of its capacity [8]. Renewable energy sources contribute less than 1.5% to its total capacity. Despite its significant role, Eskom faces challenges, including the prior mentioned problems such as the aging infrastructure, maintenance backlogs, and financial constraints. These issues often result in power outages and load-shedding, impacting both residential and industrial consumers. Which is quite an important aspect when looking at a stable and reliable electricity supply across South Africa, and in this case, Limpopo. Government corruption and a lack of skills are lacking for development efforts. In addition, conflicting authorities are granting land rights that they do not possess, resulting in disputes and instability. Meaning that the whole regulation system is quite alarming and can not be trusted. Often, these lands are later found not to belong to the granting authority, leading to significant legal and social conflicts. This situation produces more uncertainty and undermines public trust, making it difficult to implement sustainable development initiatives effectively. Addressing these problems requires severe oversight, enhanced governance, and clear legal frameworks to ensure that land allocations are legitimate and that development projects proceed smoothly.

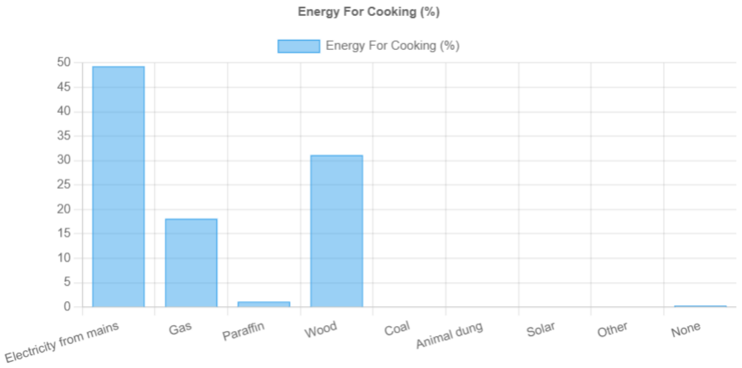


Figure 4.2: Source for energy for cooking in the whole Limpopo [71]

The current situation as shown in Fig 4.2 over the whole energy usage for Limpopo is not at all developed an ready for a quite advanced green technology. A bit more than 30% is still from wood usage as mentioned before. Looking at the local scale, in Mopani and Tzaneen, similar electricity challenges persist. These regions experience frequent power outages, often due to an overburdened and poorly maintained grid. Both areas struggle with the impacts of illegal electricity connections, corruption, and inadequate infrastructure. The reliance on illegal power sources leads to unsafe conditions and further strains the already fragile system. Since illegal tapping into the electricity grid to use power without paying is what it happening right now. This involves tampering with power lines or meters causing damage to the actual electrical infrastructure. The same goes for Phalaborwa, the urgent need for infrastructure upgrades, regional cooperation, and investment in renewable energy solutions is evident. Addressing these issues on both regional and local scales will be crucial for improving the electricity situation in Phalaborwa, Mopani and Tzaneen.

In the following chapters, I will look into strategies to improve the situation on both regional and local scales.

On a regional level, the focus will be on the biophysical properties and alternatives for the generation capacity through large-scale energy projects. These projects will not only generate higher energy numbers but also integrate sustainable practices by applying the generated power to the existing grid. Improving the grid's capacity and reliability will be crucial in addressing widespread electricity shortages. Furthermore, regional cooperation and investment in renewable energy infrastructure will be necessary to create a more resilient and self-sufficient energy system.

Locally, I will explore small-scale changes and approaches that can make a significant impact. This includes community-driven initiatives, localized renewable energy installations like solar panels on individual homes, and education programs to promote energy conservation. By combining these regional and local efforts, we can create a comprehensive strategy to improve the overall electricity situation in Phalaborwa.

4.2 Biophysical Potential on Regional Scale

In this section, I step back to assess the biophysical properties on a regional scale to explore sustainable electricity generation options. The goal is to improve the broader regional situation through renewable energy sources that therefore will create more opportunities based on a reliable system for Phalaborwa. However, such a shift depends heavily on the stance of government and municipal authorities regarding land use and funding. That said, the biophysical characteristics of the region must demonstrate the potential for solar energy, which is crucial for ensuring energy security, especially given the inconsistent supply from the Eskom grid. Additionally, this shift supports efforts to reduce carbon emissions.

In the context of post-mining activities in rural areas, solar energy can play a vital role, particularly in attracting new businesses like tourism ventures. When a mine eventually closes, any surplus electricity generated in the interim could be fed back into the Eskom grid, providing a long-term benefit to the community and supporting the region's sustainability goals.

While this shift would benefit the broader region, when considering Phalaborwa in the context of mine closures, the need for a large-scale power plant is not particularly high, as the electricity generated would ultimately be fed back into the grid. On a regional level, building 100MW plants is not a pressing priority, as the local demand does not justify such capacity. At most, a 30MW plant would be sufficient for these areas [60], especially once changes in daily energy consumption patterns are implemented. Currently, the largest electricity consumers in the area are PMC and Foskor.

Creating a new electricity-generating system requires consideration of many parameters, especially when focusing on renewable energy projects. Various energy sources, including wind, biomass, bio-fuel, geothermal, and solar, need to be evaluated to determine the most suitable option. After analyzing the potential of these sources on a regional scale, it is evident that solar energy has the highest potential for Limpopo.

Limpopo's geographical and climatic conditions make it ideal for solar energy projects. The region receives high levels of solar radiation, as illustrated in Figure 4.3, which shows an average global horizontal irradiation of approximately $2100 kWh/m^2$ in the Limpopo region. This high solar irradiation means that Limpopo can efficiently implement solar energy to meet its electricity needs.

The choice between a solar PV farm and a concentrated solar power plant would largely be an economic decision. While an environmental impact assessment is required, solar farms generally have minimal environmental impact, though potential glint and glare effects must be accounted for. However, it's important to note that solar farms create relatively few jobs. Maintenance, panel cleaning, vegetation management, and monitoring are typically handled by a small team. From this perspective, developing multiple smaller solar farms could be a better approach, as it would help provide jobs for workers currently employed in coal-based power generation.

Implementing solar energy projects in Limpopo can bring several benefits, including reducing dependency on fossil fuels, lowering greenhouse gas emissions, and providing a reliable and sustainable energy source. Solar power can also create economic opportunities, such as job creation in the construction, maintenance, and operation of solar power plants.

In summary, solar energy presents the highest potential for electricity generation in Limpopo. By using this abundant resource, the region can develop a working economy and sustainable energy infrastructure, contributing to overall economic and environmental well-being.

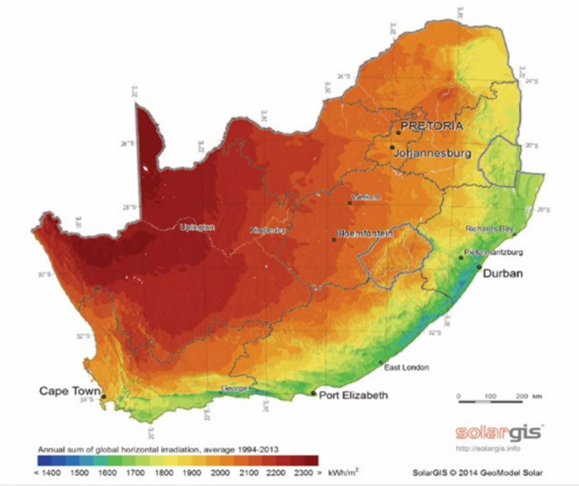


Figure 4.3: The annual sum of global horizontal irradiation [43].

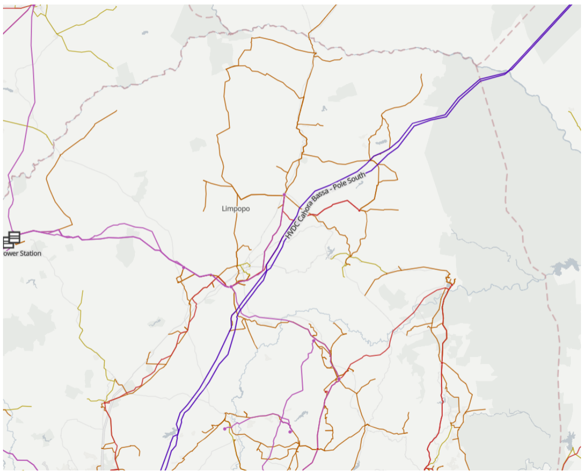


Figure 4.4: The grid infrastructure shown for Limpopo, the pipelines are 132 kV and 275 kV [58].

For the whole region of Limpopo, an alternative energy generator such as solar would be possible. The reason for it not to be determined in full detail is that it is depending on municipality, Eskom, need of electricity and land ownership. This will be correlated to water availability and agriculture. It is a very great perspective that it is not scarce and that it is depending on all factors but solar irradiance since there is enough in the whole region.

	Limpopo	**Phalaborwa**
Electricity Supply	96.4% from Eskom	no data
Electricity Demand	no data	no data
Nr. of Households	1,811,565	49099
Employment Rate (economically active)	61.4%	39%
Coal / Grid / Gas based	95%	100%
Renewable based	5%	0%
Population size	6,572,721	168937

Table 4.1: Some indication of the Limpopo and Phalaborwa region [71], [2] [3], [77].

In the Table 4.1 it shows that Eskom is the big dominator of the region and that there is very little data available. Also the data that is available is outdated and not accurate to all people living there but it has a certain bias. Another thing to notice is that there hasn't been much implementation of solar plants up to this date. This can be due to other issues and the need of other developments before solar plants are the most demanding change in the region. In Fig 4.3.4 the infrastructure of the present is shown. Showing 132 to 275 kV pipelines. There is a great connection to Phalaborwa since the mine is in need of a high amount of electricity and over the region there are connections as well. To transform the capacity of the pipelines to the wattage of solar electricity that could be generated we use the following formula:

$$\textbf{Power (P)} = \textbf{Voltage(V) x Current(I)} \tag{4.1}$$

Looking at the maximal capacity, the current for a 275 kV line can range between 3000 to 5000 amperes (A) [41]. This means that the maximal capacity, using 5000 A would be:

$$\textbf{Power} = \textbf{275000 V x 5000 A} = \textbf{1375 MW} = \textbf{1.4 GW} \tag{4.2}$$

The number $1.4GW$ shows that when a solar power plant of 100 MW will be installed it can be transported by the already existing pipelines. The 132 kV lines are typically used to transmit electricity from generation sources to local substations, these are not shown in Fig 4.3.4. The 275 kV lines are used to transport electricity over longer distances to regional substations, shown of the map. Once electricity reaches regional substations, it is stepped down to lower voltages for distribution to consumers as shown in Fig 4.5. The distribution network operates at medium to low voltages to safely deliver electricity to homes, businesses, and industries. These medium voltages range from 1 kV to 33 kV. This voltage level is used to distribute electricity to local substations closer to end-users. The low voltages, generally less than 1 kV, is used for the final delivery to consumers [41]. Eskom and local municipalities are investing in infrastructure upgrades, implementing advanced monitoring systems, and enhancing security measures since this infrastructure needs improvements.

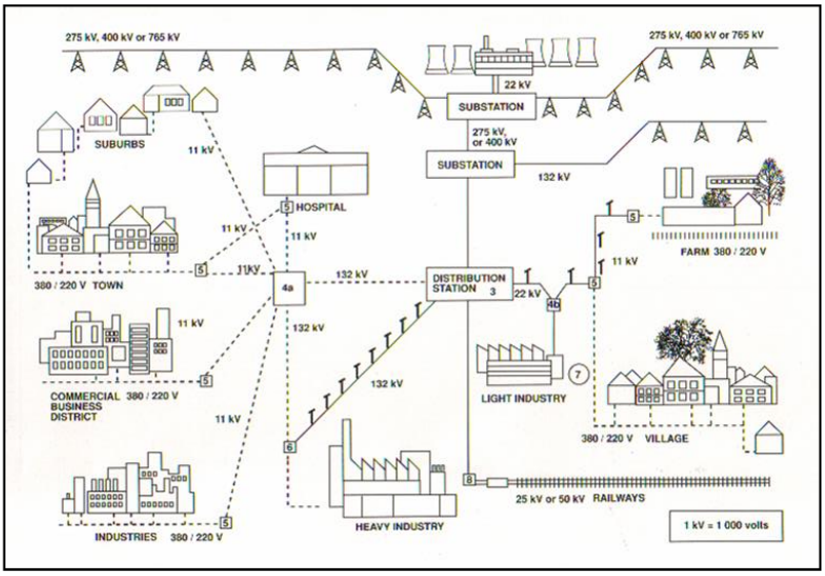


Figure 4.5: The infrastructure, system of medium to low voltages [41].

4.2.1 Demand and Supply

Phalaborwa Supply and Demand

In Phalaborwa, the Phalaborwa municipality delivers electricity in the urban centers, whereas Eskom mostly supplies energy in distant areas (such as Namakgale and Lulekani) [6]. There are over 4,000 connections in the Phalaborwa network, serving both major industrial and residential users with different needs. Nevertheless, there is a greater chance of service interruptions due to the old infrastructure, some of which is over 40 years old [6]. There are 2250 houses in the municipality that still need to be connected due to the electricity gap. Approximately 97.7% of households, or 50468 households, have access to electricity; however, 153 households do not. The demand for electricity has increased over the years, especially due to growth in the mining and industrial sectors. Peak electricity demand in the Phalaborwa Customer Load Network (CLN) is expected to grow from 1756 MW in 2022 to 2278 MW by 2029, reflecting a steady annual increase [30]. Meaning that there is growth going on and it will be more in the future. However, this growth does not necessarily means that the communities / townships are developing or growing as well. Which is creating a very diverse economy and a very diverse way of living.

Regional (Limpopo) Supply and Demand

The energy supply is a combination of the grid operated by Eskom, which mostly relies on coal-fired power plants, and renewable energy sources like solar photovoltaics (PV) providing Limpopo with electricity. Three solar PV facilities, Tabor (28 MW), Witkop (30 MW), and Matimba (60 MW), have been integrated [30]. With projects like the Nzhelele Transmission Substation [70] being created to handle new mines and residential developments, the energy infrastructure is gradually being improved [30]. The total yearly growth rate of Limpopo's electricity demand is approximately 4.03%. The main drivers are mining, residential development, and industrial activity. For instance, it is anticipated that the Polokwane CLN will grow by 2.81% and the Lephalale CLN by 4.24% [30].

Existing Plans and Infrastructure for Phalaborwa and Limpopo

Plans for the Phalaborwa region are in place to modernize Phalaborwa's poor infrastructure, which will involve replacing 11kV switchgear, updating substations on a selective basis, and fixing serious supply line problems. However there are some issues that include unreliable 11kV switchgear and circuit breakers, which pose safety risks. Capacity constraints exist, particularly at the Selati main intake substation, which struggles to handle peak loads during periods of heavy demand. Approximately 70 solar-based high mast lights have been installed across wards to provide lighting in rural areas. There remains an electrification backlog, primarily in rural villages. The backlog includes areas like Makhushane and Lulekani, which require grid connections [6]. The municipality plans to keep installing solar and LED energy-saving lighting solutions, particularly for public illumination. Recent grid integration of solar PV plants demonstrates Limpopo's growing reliance on renewable energy as part of its energy transition. The incorporation of renewables is consistent with national aspirations to reduce carbon emissions. In order to accommodate rising demand and include additional renewable energy sources, Eskom has pledged to continue developing the transmission network [30]. This knowledge gives hope for the future and shows that the people are open for change and already experiencing it.

Limpopo has to two major coal-fired power stations, Medupi and Matimba, located in Lephalale. Together, these stations provide 8.5 GW of electricity to the grid. Medupi, when fully operational, will be the world's largest dry-cooled power station, generating 4356 MW [30]. Limpopo is incorporating renewable energy sources into its grid. Three solar PV plants have already been integrated as mentioned before:

- Tabor PV Plant (28 MW): Connected to Tabor Substation.
- Witkop PV Plant (30 MW): Linked to Witkop Substation.
- Matimba PV Plant (60 MW): Integrated into Matimba Substation in Lephalale

Various grid expansion projects are underway to accommodate future growth in demand. For example, the Nzhelele 400kV integration project is aimed at enhancing capacity by building new 400kV transmission lines and substations to de-load the Tabor and Spencer Substations. The Northern Grid, which covers the Phalaborwa area, includes substations interconnected by 400kV, 275kV, and 132kV lines. Peak load in this region is expected to grow due to industrial expansion, particularly in mining. When looking at these existing plans, there is room for change. What you do see is that the solar PV plants are still on a 'smaller' scale than when we are talking about 100 MW.

4.3 Potential on Local Scale

In this section I will be looking at possible opportunities and challenges on a local scale. What is possible in Phalaborwa and what is needed to transition to a better future? I will be looking at solar mini grids, off gird solar systems, agrovoltaics, solar geysers, and use some case studies.

4.3.1 Solar mini grid

Case study 1: Solar mini-grid transforms lives of Zimbabweans in rural areas and how they can be applied to Phalaborwa [26].

The project in Chipinge, Zimbabwe, involved a 200 kW solar mini-grid, shown in Fig 4.6, that powers over 100 homes and businesses [74]. The mini-grid has transformed the lives of locals by providing reliable electricity, giving new business opportunities, and improving the quality of life [26]. The project aligns with Zimbabwe's sustainable energy goals and shows the potential for decentralized renewable energy solutions. The project was a collaborative effort involving government, private sector, and international donors [67]. Access to electricity has allowed residents to start small businesses, such as carpentry, which contributes to local economic growth.

Figure 4.6: The solar mini grid in Zimbabwe [26].

By looking at this example, and what the situation is in Phalaborwa we can conclude that Phalaborwa can benefit from a similar 200 kW solar mini-grid to provide reliable electricity to homes, schools, and businesses. This would address the current electricity shortages and improve the quality of life for residents. Meaning that engaging the local community in the planning and implementation process can ensure that the project meets their needs and gains their support and will create jobs for the local residents. Providing electricity can stimulate local economic growth by enabling residents to start small businesses and improve existing ones, providing a future with hope. By implementing on this local scale such projects, it can contribute to Phalaborwa's and South Africa's broader sustainability goals by reducing reliance on fossil fuels and promoting renewable energy which gives a chance to collaborate with government agencies and private companies.

4.3.2 Solar Geysers

Case Study 2: Household-Scale Solar Geyser in Pretoria, South Africa [59].

A household in Pretoria, South Africa, implemented a solar water heating system with a 1.575 kWp solar PV array. The system provided over 50% of the family's water heating energy, even during winter. This setup significantly reduced their electricity consumption and lowered their energy bills [27]. The solar geyser system included solar collectors, a storage tank, and necessary plumbing [38]. The family size was four people, and the system achieved a solar fraction of 52%. Shown in the Fig 4.7 and Fig 4.8 is the distribution of the solar electricity usage. This is for the case of a family of 4 in 2017.

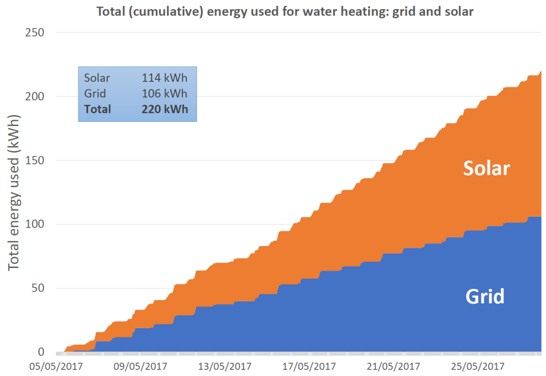


Figure 4.7: Total energy used by a household of 4 in 2017 making a difference between energy from the grid and energy from solar [59].

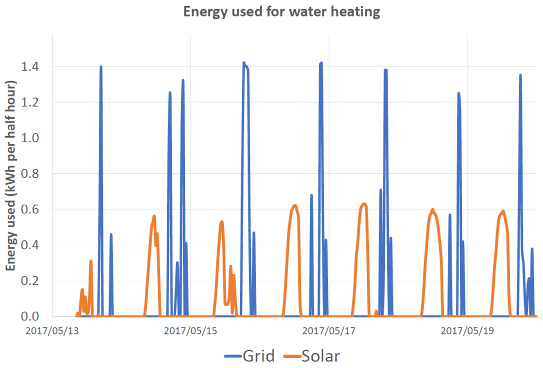


Figure 4.8: Total energy used for a household of 4 in 2017 looking at the grid supply and solar supply [59].

Another example is shown in Fig 4.9 and Fig 4.10 is how it developed over the years, this is for a 1 person home but showing how solar is the dominant generator for his household in winter, which is a great difference from summer. Over 75% of this households water heating was supplied by the sun [59]. This was located in Johannesburg and the solar PV array size was 1.5kWp. Showing that individual changes can definitely be made and are working on a small scale.

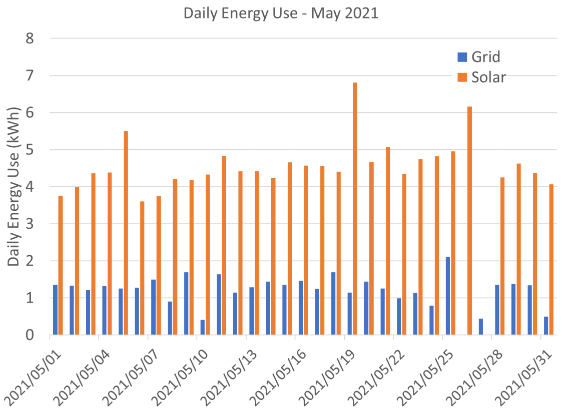


Figure 4.9: The daily energy use of a household of 1 person in 2021 [59].

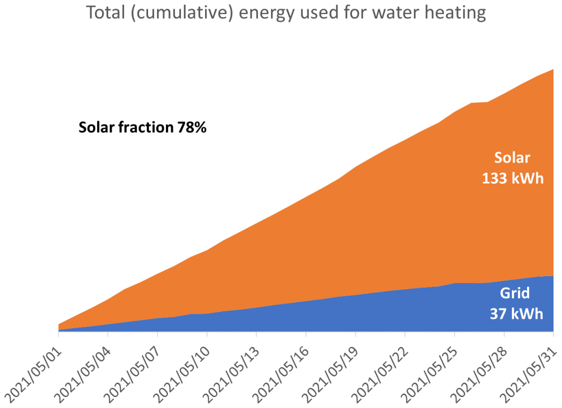


Figure 4.10: The total energy used for water heating in a 1 persons household in 2021 making a difference between solar and the gird supply [59].

When we look at all graphs, it is very interesting to see that in 4 years time there is already a big increase on solar energy usage and independency from the grid in Pretoria. What is visible is that at the end in May 2021 the electricity from the grid is barely used and that solar is the dominant electricity provider. Meaning there is a growth in solar electricity and the technologies also keep evolving. Especially when looking at the energy used for water heating, it has where it was prior (in 2017) dominated by the grid as supplier now turned to solar.

These devices function as energy managers with advanced sensors and controls. They effectively use excess solar energy for water heating without interfering with other appliances' ability to use energy. With cost savings and several clear environmental advantages, their energy efficiency is demonstrated by the smart scheduling of water heating during solar energy production's peak, which reduces dependency on the grid and promotes enhanced energy optimization. Showing an decrease in payback period when increasing the size of solar panels shown in Fig 4.11.

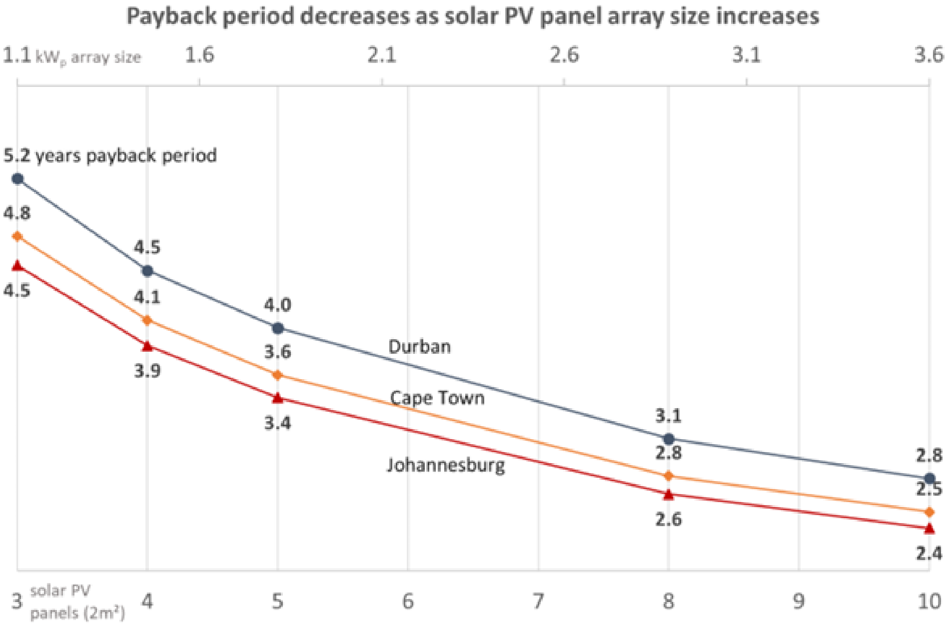


Figure 4.11: Payback period of a 1.1 kWp array size in the different locations in South Africa. Shown that the time decreases when increasing the number of solar panels.

What is interesting in Fig 4.11 is to notice that location does have an impact on the efficiency of the solar panel. As shown in Fig 4.3 is Durban located in a low potential area for solar panels. Johannesburg and Cape Town have higher potentials around the $2100kWh/m^2$. This is beneficial for the usage, since the payback period will be 2.4 years in Johannesburg when installing 10 solar PV panels $= 20m^2$. Since The area in Limpopo, Phalaborwa is around $1900kWh/m^2$ its payback time will be slightly higher, but not higher than Durban's payback time since the solar irradiance is significantly lower in that area.

Case Study 3: Quantification of the Impact of Solar Water Heating and Influence of Its Potential Utilization through Strategic Campaign in Dimbaza, South Africa [34].

In Dimbaza, an experiment was conducted in a household with four adults to monitor the performance of an electric water heater, called a geyser, and a Solar Water Heater (SWH) as shown in Fig 4.12 with an auxiliary electric heater. This SWH is the same as a solar geyser, just different naming.

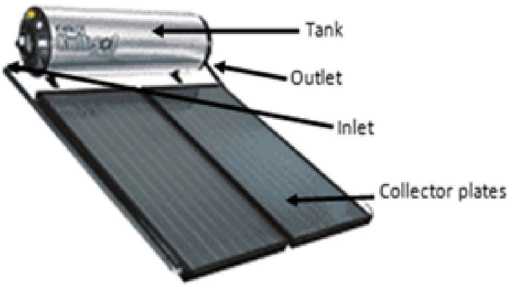


Figure 4.12: A flat plate collector Solar Water Heater [34].

Sensors measured temperatures at the inlet and outlet of the water tank and collector, while a power meter tracked the electricity consumed by both heaters. A flow meter recorded the water usage, and additional sensors measured solar radiation, ambient temperature, and humidity. All data was logged every five minutes using a 15-channel data logger housed in a waterproof enclosure. The reason for implementation of the SWH with the geyser is to reduce the electrical energy consumption by obtaining hot water. The Eq 4.3 shows us the useful thermal energy gained by day is equal to the global solar irradiation for the day and the collector's efficiency and its total collector area.

$$Q_u = G\eta A_c \tag{4.3}$$

These measurements were done and a survey was conducted in January 2022 with 150 households in Dimbaza, all using electric water heaters. During the first week, participants were informed about potential monetary savings from switching to SWHs. In the second week, the focus was on the environmental and health benefits of SWHs. The final week combined both aspects; financial savings and environmental benefits. The survey aimed to measure residents' readiness and interest in transitioning to SWHs.Shown in Fig 4.13 are the results of the study and it is showing that the geyser has consumed an average of 19.55 kWh per day, resulting in the heating of 240 liter of water. Where the SWH consumed 11.73 kWh per day for 243 liters of water. This study found that the hybrid SWH had a net present value payback period of 4.32 years, reducing annual energy consumption for hot water heating by 40%.

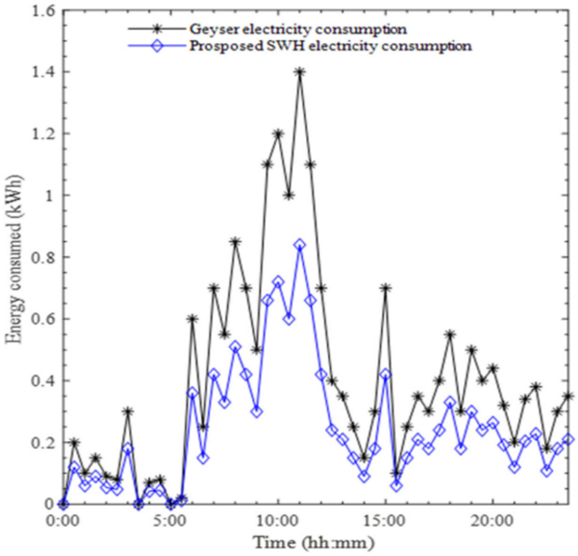


Figure 4.13: The average month day electrical energy use of the geysers and SWHs [34].

4.3.3 Agrovoltaics

Agrovoltaics, or agrivoltaics, involves the use of a land for both agriculture and solar photovoltaic (PV) power generation, optimizing land use by allowing crops and solar panels to coexist. This innovative approach increases land productivity, economic opportunities, and environmental sustainability. In Phalaborwa, implementing agrovoltaics can significantly contribute to electricity generation by mounting solar panels at elevated heights of 2-3 meters to allow sufficient sunlight to reach crops below. The panels are optimally tilted between 20 to 40 to balance energy capture and crop growth. Shade-tolerant crops, efficient irrigation systems like drip irrigation, and effective water management strategies, such as rainwater harvesting, can further enhance sustainability [78]. Integrating battery storage systems allows for the storage of excess electricity generated during peak sunlight hours, ensuring a continuous power supply. Grid integration, which is another topic discussed in 4.3.4 , enables the sale of excess electricity, providing a reliable local energy source. The economic benefits include job creation in construction, maintenance, and operation, as well as opportunities for local farmers and entrepreneurs in producing crops and engaging in agro-tourism activities. By implementing agrovoltaics, Phalaborwa can achieve sustainable and efficient land use, improve electricity supply, boost agricultural productivity, and support local economic development [23]. This integrated approach, characterized by its technical precision and community engagement, can serve as a model for other regions with similar challenges. Because the case as of right now in Phalaborwa is shown in Fig 4.14 and can use some improvements.

Figure 4.14: The local solution for agriculture and landuse.

Implementing agrovoltaic systems in Phalaborwa can help meet the region's electricity needs while utilizing the available land efficiently. This can contribute to a more reliable and sustainable energy supply and which is kept locally.

4.3.4 Off the Grid Generation

In the paragraphs above we talked about system to apply for oneself. However there are some regulations that need to be taken into account when being a electricity generator. This is for small and large scale. An Independent Power Producer (IPP) is therefore a system that is set in place between producer and Eskom. It enables third-parties to transmit energy across the grid and offset their consumption, improving flexibility for independent producers. In Fig 4.15 you see that there is a trade between what you use from the grid and what you give back to the grid. The usage is property from Eskom and what you give back is self-generated electricity.

Use-of-system charges, often called wheeling charges, apply to all energy delivered to customers over the grid network, regardless of whether the energy is supplied by Eskom or a third party. These charges reflect the cost of grid usage and are therefore unavoidable, ensuring that all customers contribute equally to grid maintenance. Conversely, loads pay use-of-system charges on energy drawn from the grid, while only non-Eskom-supplied energy is credited on a customer's account as wheeled energy, excluding any use-of-system credits.

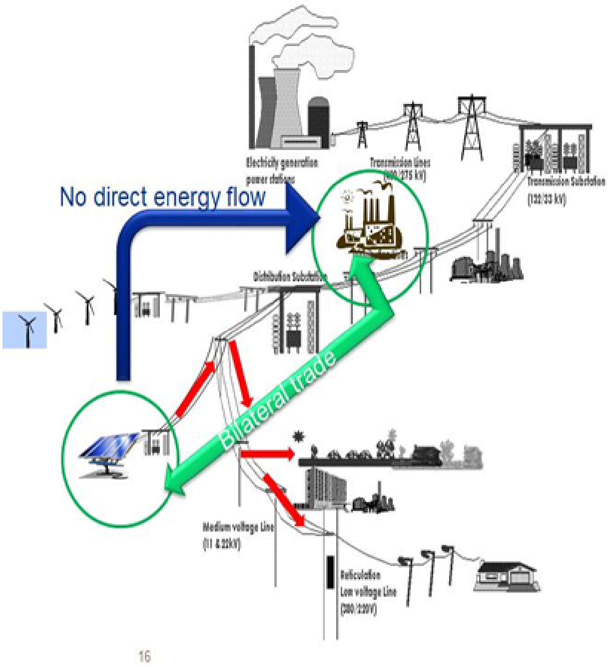


Figure 4.15: System of energy flow in such circumstances as an IPP [29].

For an IPP in South Africa's growing energy demands, it has led the Department of Mineral Resources and Energy (DMRE) to explore options to increase power system capacity, emphasizing IPP and private sector involvement. A key initiative is to obtain sustainable energy through public and private partnerships. In June 2021, the Minister of Mineral Resources and Energy proposed amending the Electricity Regulation Act to allow businesses and individuals to generate up to 100 MW without a NERSA license, provided they follow the regulations regarding distribution and transmission and maintain a connection point. To get through with this 100 MW plant you do need to go through a whole process of application.

In Fig 4.16 it shows how on a local scale the wheeling happens. Since we have been talking about self generating for households and solar panels, geyser, agrovolatics and more. The electricity that is generated but not being used can be given back to the grid. So what is happening is called 'net-billing'. Net billing allows customers to receive a credit on their electricity bill for surplus energy they generate but do not immediately consume. This credit is typically provided at a rate similar to the utility's avoided cost of fuel, or sometimes slightly lower than the energy-only charge. A single bidirectional meter records both the customer's energy usage and any excess energy exported back to the grid. Importantly, this excess energy is not sold; it remains the customer's property, allowing them to use the grid as a form of battery storage, offsetting future energy costs. Which is a great solution for when it is dark and there is no sun, the households can use electricity from the grid but it will be free. Only costs are for usage of their grid [31].

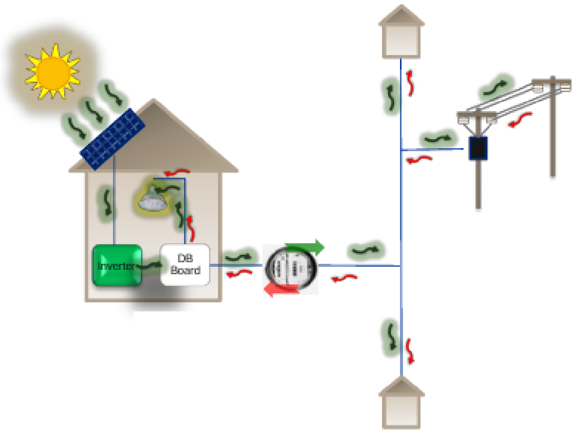


Figure 4.16: A household owns and operates an electrical generating device and this is working in sink with the grid tied system [29].

This system is a win-win situation and can create a whole movement if everyone would slowly adapt to this system. Not only companies such as PMC will then benefit from such regulations but also the regular people from the communities.

4.3.5 Challenges with Residential Solar PV

When looking at changing the infrastructure and the organisation of energy supply in such areas, challenges are occurring. Despite favorable climatic conditions for solar energy, adoption rates remain low, particularly among low-income households. The high capital investment required for installing solar PV systems is a significant barrier. Which is totally understandable and, as prior mentioned, with the current situation of cooking on wood to transition to a solar panel is almost unimaginable. Despite the potential benefits, the adoption of residential solar PV systems in South Africa is low, with only about 10% of households having adopted solar energy [24]. The transition to solar PV adoption is hindered by various barriers that directly affect low- and medium-income groups which is the problem of society, that change is very difficult for these groups. In the case of Phalaborwa, like many other regions in South Africa, it faces similar challenges with electricity supply and affordability. Implementing residential solar PV systems in Phalaborwa could help address these issues, but it is crucial to then start by having subsidies, financing options, or motives that can help make solar PV systems more affordable for low-income households in Phalaborwa. Second of all, engaging the local community in the planning and implementation process can ensure that the project meets their needs and gains their support. Which creates a sense of hope and a will to change for a better day to day living and future.

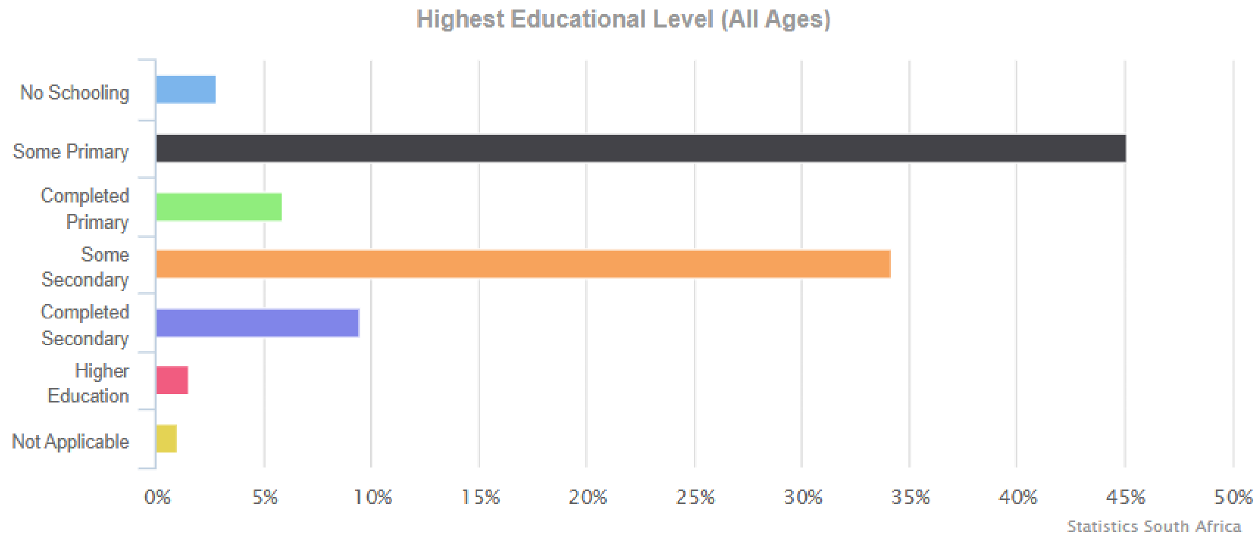


Figure 4.17: Statistics on Phalaborwa on highest education level for all ages [71].

Another issue to consider is the general lack of knowledge about new technologies, such as solar energy systems. Educating residents about the benefits of solar energy and how to use and maintain solar PV systems can significantly increase adoption rates. As shown in Fig 4.17, Phalaborwa faces a substantial skills gap, with only 1.5% of the population having attained higher education. This deficit in education is problematic when attempting to implement and manage advanced technologies. The low prioritization of schooling and technical training makes it harder to implement change, making it challenging to build a workforce capable of supporting sustainable development initiatives. Comprehensive education and skill-building programs are essential to address these gaps and enable effective transitions to modern, sustainable technologies. More will be elaborated on this topic in Section 4.3.6.

4.3.6 Challenges with Education and Change

In Phalaborwa, South Africa, residents face several challenges in transitioning to a sustainable future. Limited access to quality education and persistent socio-economic inequalities hinder progress. Many schools lack qualified teachers, especially in critical subjects like math and science, and large class sizes prevent individual attention. Additionally, social issues such as child-headed households, teenage pregnancy, and HIV prevalence further complicate efforts[25]. Analyzing the statistics from Phalaborwa shows some alarming trends regarding employment and internet access. Less than 50% of the population is employed, and a significant portion of individuals are not actively seeking work, as illustrated by the orange graph in Figure 4.19. In terms of internet access, the situation is equally concerning. Limited connectivity prevents residents from keeping up with global trends, understanding expectations, and recognizing opportunities. Their world remains confined to their immediate surroundings. This lack of exposure to different ways of living and working presents a major issue in transitioning to a sustainable future. Effective change in such communities will require substantial effort and resources to introduce and normalize new concepts and technologies.

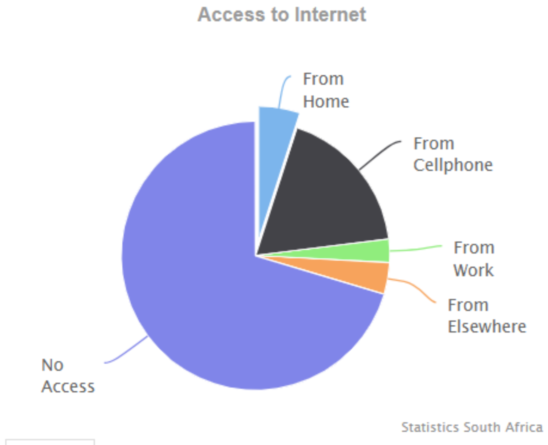


Figure 4.18: Access to internet in Phalaborwa [71].

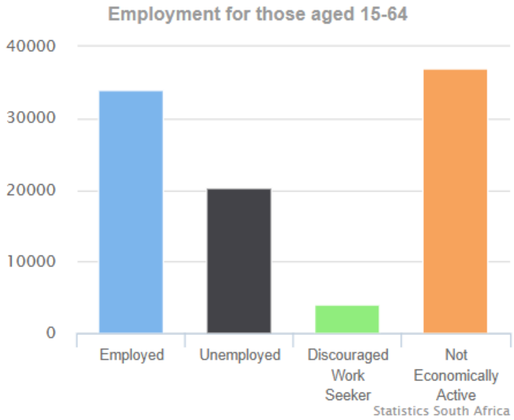


Figure 4.19: Employment rate for Phalaborwa [71]

Another factor to consider is the linguistic diversity in the region, with English not being the primary language for many residents. This language barrier poses significant communication challenges, especially when dealing with foreign-owned companies, such as those from China. Additionally, the data highlights a critical skills gap within the population, underscoring the urgent need for improved education and training programs. Addressing these issues is essential to facilitate effective communication, enhance skill levels, and ultimately support the transition to a sustainable future in Phalaborwa.

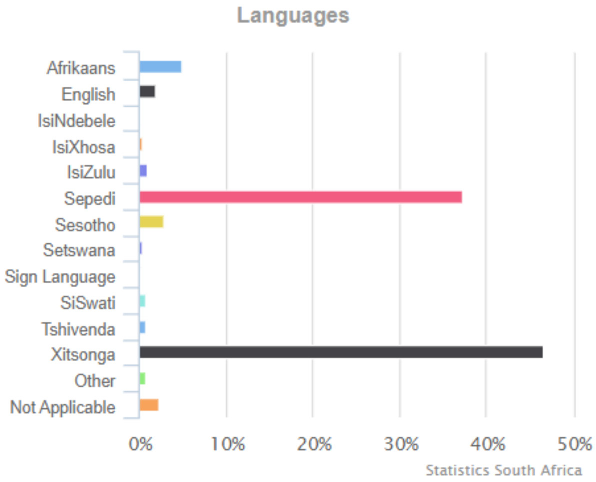


Figure 4.20: Languages [71]

4.4 PMC Energy Generation

4.4.1 The current situation

The current situation at Palabora Mining Company (PMC) in Phalaborwa is focusend on the extraction and processing of copper and the production of vermiculite and magnetite. This is done by block caving, the current project is the "Lift II Block Cave Project". This is 450 meters beneath Lift I and this project has the aim to extend the life of the underground mine up to 2033. They also make use of a ventilation shaft, at 1200 meters depth to provide fresh air to the underground operation [45]. There are studies/exporations for a third shaft which would mean that the life would be extended to 2050, said by Johan (PMC).

To pursue these goals, electricity is needed. Their current primarily source is electricity from the Eskom grid. Their annual bill is around R500 million = \$30 million. This means that the annual consumption and daily consumption is the following given that the average electricity tariff in South Africa is R2.40 per kWh [32].

$$\textbf{Annual Electricity Concumption} = \frac{R500million}{R2.40/kWh} = 208.33GWh/year \tag{4.4}$$

$$\textbf{Daily Electricity Consumption} = 570.78 MWh/day \tag{4.5}$$

These amounts are very high and are on another level, industry, and not local and community scale. When comparing it to the communities in Phalaborwa, it is a humongous amount that they will never need of. The most as mentioned before would be a 30 MWh/day plant. Meaning that if the PMC would decide to stop operating, and giving back the electricity to the grid to Eskom, that there would be enough for the communities and other businesses such as tourism. This would be in the case of mine closure and post mining activities and new business are founded.

During discussions with Johan, we learned that PMC is conducting a feasibility study for the installation of an on-site solar plant capable of generating 100 MWh/day as an independent power producer.

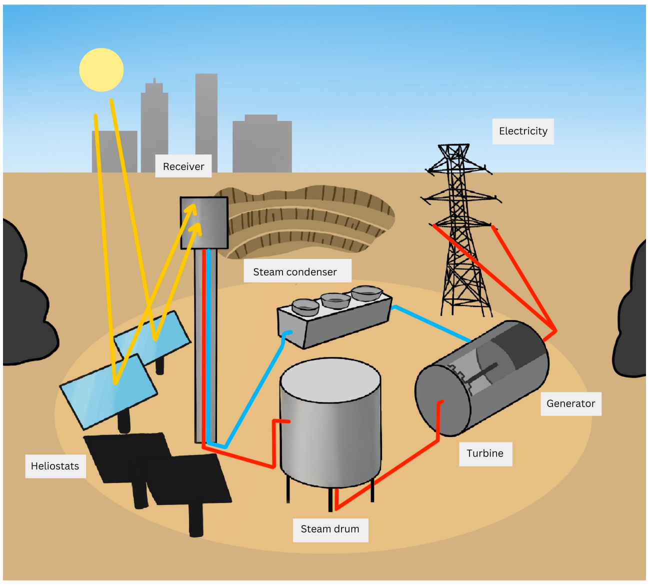


Figure 4.21: A feasible idea for the PMC mine.

This aligns with Eskom's regulation permitting private landowners to generate up to 100 MWh/day for private use only, without the ability to sell this electricity to other customers or create a private grid. This will cover only part of their daily consumption. A general guesstimate is that 10000 m^2 of land use is needed for 1 MW of capacity [57]. This means that around 41700 m^2 is needed with 13900 solar panels since, assumed one is 2 m^2 and generates 300 W, the total capacity is 4.17 MW. This is when assuming it to be a grid-connected solar photovoltaic system.

In Fig 4.21, a demonstration of a concentrated power system(CPS) is provided. This is another option that could work in the area. Since PMC did not disclose specific details about the project, this figure is a speculative representation. Since their focus is on energy management programs to reduce its energy costs [44]. However, when taking the same numbers for the guesstimates for the PV solar farm, the CPS needs a lot more of land. As shown in Fig 4.22.

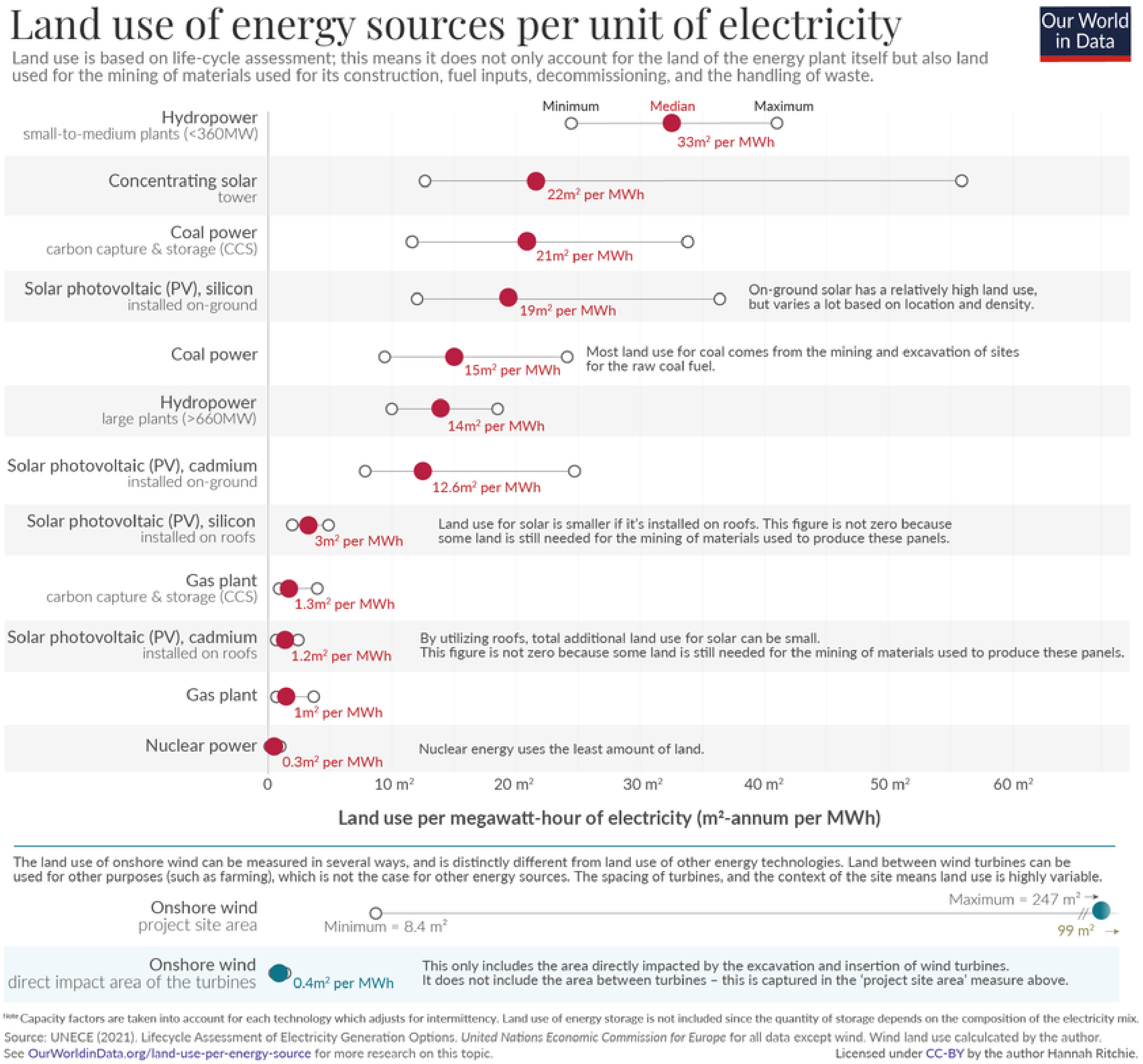


Figure 4.22: The different systems of energy generation and their land use.

4.4.2 Re-purposing post mining land for alternative energy sources in Phalaborwa

The land currently occupied by PMC and its associated tailing dumpsites (Selati and East tailing and waste rock drainage) in Phalaborwa can be used as a great opportunity for sustainable redevelopment after mine closure. Given that the soil in these areas is largely affected by the toxic elements and has no agricultural value due to extensive mining activities, re-purposing this land for solar energy generation is both a sustainable and practical solution. Using these post mining sites for solar farms will optimize land use. This transformation of degraded land into productive, electricity generating areas will then be the future. Another benefit is from the economic aspect. Establishing solar farms on these sites can create economic opportunities. Job creation during the construction, maintenance, and operation phases can provide employment for local communities, contributing to economic growth and stability. Beyond economic and environmental benefits, solar farms can improve the quality of life for residents by providing a reliable and sustainable energy source. This can stimulate local economic growth, encourage new business ventures, and attract investment in other sectors, such as tourism and agrovoltaics.

4.5 WEF Nexus Discussion

Phalaborwa, located in Limpopo, South Africa, is a region with significant mining activities, primarily centered around the Palabora Copper Mine. The mining industry has historically been the backbone of the local economy, but it has also posed environmental challenges. The Water-Energy-Food (WEF) Nexus approach has been used in addressing these challenges and looking at sustainable development in the region.

The WEF Nexus approach shows the interconnections between water, energy, and food systems and aims to manage these resources in a sustainable and integrated manner. In this case, this approach has been applied to look at the region's electricity needs while considering the impacts and solutions regarding the resources of water and food and its security.

Agrovoltaics is an innovative approach that integrates photovoltaic (PV) systems with agricultural land, so that the production of crops and solar energy can be generated at the same time. This dual-use of land optimizes resource efficiency. By installing solar panels above crops, agrovoltaics can provide shade and reduce water evaporation, potentially improving crop production in arid climates. Another integration is the use of post-mining land for solar farms optimizes land use and mitigates environmental degradation.
For the water scarcity, the capture of water by JoJo tanks can support the solar geyser systems. The water can be integrated and provides a sustainable source of hot water for domestic use.

The WEF Nexus approach has played a crucial role in addressing the electricity challenges in Phalaborwa and Limpopo. By using the WEF Nexus approach, integrated and sustainable resource management, the approach has provided insights into optimizing resource use, providing energy security, and supporting economic and environmental well-being.

A critical discussion point for the energy sector in Phalaborwa and Limpopo is the involvement of a wide range of stakeholders in creating a stable and sustainable future. The complexity of the energy challenges in this region means that solutions cannot rely solely on technological advancements such as solar panels. Instead, it requires a holistic approach that addresses underlying socio-economic and political issues.

Government intervention is essential in creating supportive policies and regulations that encourage renewable energy adoption. This includes providing subsidies, incentives, and smooth processes for independent power producers. Local communities must be actively involved in the planning and implementation of energy projects. This ensures that the solutions meet their specific needs and create a sense of ownership and support for these initiatives. Private companies have a crucial role in investing in renewable energy projects and bringing technological innovations to the forefront. Their involvement can provide the necessary capital and expertise to drive these projects forward. NGOs can facilitate education and awareness programs, helping to bridge the skills gap and promote the benefits of renewable energy solutions. They can also advocate for the rights and needs of poor communities.

Another aspect is corruption. Corruption undermines the effectiveness of energy projects and hinders progress. Strict oversight, transparency, and accountability are necessary to ensure that resources are utilized efficiently and for the intended purposes. Poverty and socio-economic inequalities create more energy challenges. Efforts to improve access to quality education and economic opportunities are essential in empowering communities and stimulate sustainable development. Beyond energy, investments in water and food security are also crucial. Integrated solutions that address the Water-Energy-Food (WEF) Nexus can create synergies and enhance overall resource management.

The path to a stable and sustainable energy future in Phalaborwa and Limpopo requires teamwork from multiple stakeholders. Addressing the deep-rooted issues of corruption and socio-economic imbalance is as important as advancing renewable energy technologies. Only through collaborative and comprehensive approaches can the region achieve its sustainability goals and improve the quality of life for its residents.

Chapter 5

Food

Introduction: the context of agriculture in Mopani

Ensuring food security in Mopani, from Tzaneen to Phalaborwa, is challenging primarily due to arid conditions and the lack of skills among subsistence farmers. Regardless of the future of Palabora Mining Company and its consequences to the surrounding towns, it's important to consider the agricultural future of the lands between Tzaneen and Phalaborwa. What remains feasible? Which lands hold potential for commercial farming, and which are relegated to low-yield communal farming? And how can these less productive lands still be used most effectively?-this chapter gives answers to such questions.

Currently, most of the food consumed in Phalaborwa is imported. After all, the state of agriculture in Phalaborwa is meager, quite literally, because the yields are low and solely for communal use. Export is non-existent. This is partly explained by the limited potential of the soil. Consequently, farmers by profession are scarce and those who call themselves apt ultimately lack an understanding to deal with the limited potential of the soil and its biophysical parameters. Sophisticated techniques, such as drip irrigation, are countered by borehole exhaustion. And some small-scale farms use the necessary fertilizers excessively, and even worse, incorrectly.

All in all the form of agriculture in Phalaborwa is a type of subsistence farming. These communal farms cultivate, among other crops, tomatoes, cabbage, carrots, lettuce and onions. Some farms grow papaya and mango trees. These communal farmers make freely use of fertilizers and pesticides, as result of the limited potential of the soil. Some farmers cultivate fully organically. The necessity of fertilizers is evident. The arid conditions, limited water supply, and high temperatures require artificial supplements for farming to be successful. Without these additives, the communal farms would revert to their natural, uncultivable state. The meagre potential of the soil is further limited by the scarce and interrupted supply of water. Corrosion of water pipes and irresponsible management incentivises farmers to look for other water sources closer by, namely boreholes. Boreholes are, however, not sustainable and risk depletion at any moment. Thus, scarce water supply and enthusiastic use of fertilizers make the career of a subsistence farmer highly unstable. Consequently, for Phalaborwa to guarantee food safety and sufficient supply an external source is necessary, for example, others parts of the Mopani region.

Phalaborwa is situated on the eastern side of Mopani. The Mopani district in its totality, in opposition to the municipality of Phalaborwa and its minimal and meager forms of agriculture, bears more potential for farming. On the western side, round and about Tzaneen, industrial forms of agriculture produce tomatoes, bananas, papayas, mangos, avocados and citrus fruits.

This chapter delves into the biophysical state of Mopani and explains the remarkable fact that, within just 100 kilometers of each other, some of South Africa's most barren land (Phalaborwa) and its most fertile farmland (Tzaneen) are located side by side. Using satellite data and soil models and maps, a preliminary answer is provided to explain the biophysics of Mopani (Chapter 5.1). Chapter 5.1 has an engineering perspective and is organised rather conventionally, by stating the problem, providing a methodology, giving the result and discussing the limitation of the research. Chapter 5.2 will elaborate on the practice that can develop from the biophysical knowledge attained in Chapter 5.1, by providing two case studies. The first study (Chapter 5.2.1) focuses on how commercial farming in Tzaneen can expand its agricultural lands, paired with modern energy solutions (agrivoltaics). This expansion could serve as a model for improving agricultural practices in the region. Additionally, in the second case study (Chapter 5.2.2), it will explore how subsistence farming in Phalaborwa can enhance the meager forms of agriculture currently practiced on soil with limited potential.

5.1 Preliminary characterisation of soil properties

The goal of this preliminary investigation is to develop a methodology capable of predicting nutrient levels—most notably, nitrogen concentration—of a given land area using satellite imagery. To this end three vegetation indices are compared with an existing nitrogen concentration map to identify the most suitable method. Modeling nitrogen concentration maps is worthwhile, because both commercial and subsistence farmers use it in their fertilization strategies. With near real-time maps of farmlands, farmers can pinpoint which areas require more fertilization, ensuring efficient use of resources across different sections of the land.

The endeavour to characterise soils and their properties is a noble pursuit—knowledge of soils is essential to limit the use of fertilizers and to optimize yield. Any given soil possesses distinct characteristics and understanding these enables farmers to cultivate their land most effectively. Noble turns into vain, however, when an incomplete characterisation of the soil leads to invalid conclusions. The data is scarce and limited, and in-situ measurements of the soil properties are required to attain a 'complete characterisation of the soil'. Thus, from the perspective of our research, it is vain to pursue said 'complete characterisation'. Throughout the chapter these limitations become clear and are summarised by the end. These pessimistic words are not meant to discourage the reader or to implant the idea that the characterisation was useless. The reader discovers by chapter's end that, in fact, conclusion can be drawn from limited data, but that vanity lurks around the corner when those inferences are treated as the true and final characterisation.

5.1.1 Methodology

Data sources and processing

The research uses two types of data: Sentinel-2 satellite imagery and soil data from SoilGrids.org. "Sentinel-2" rasters provide high-resolution (10m, 20m, 60m.) and multispectral data suitable for vegetation analysis. The Sentinel-2 L2A (L2A: atmospherically corrected) rasters were sourced from the Copernicus Open Access Hub for each season (March, June, September, and December) and processed using ESA's SNAP software [14]. The processing workflow for each season involved the following steps: resampling to 10.0 meters, creating a multi-size mosaic, and calculating indices (NDVI, EVI, RE-OSAVI). In addition to the satellite data, nitrogen content maps were obtained from SoilGrids.org, a platform that offers soil property predictions at various depths based on global soil data and machine learning algorithms [35].

Calculation of Indices

To characterize agricultural lands effectively, three vegetation indices, namely the Normalized Difference Vegetation Index (NDVI, eq. 4.1), Enhanced Vegetation Index (EVI, eq. 4.2), and Red Edge Optimized Soil Adjusted Vegetation Index (RE-OSAVI, eq. 4.3) were calculated from the Sentinel-2 imagery. A nitrogen index (Eq. 4.4) was modelled using the SoilGrids nitrogen map and bulk density map.

1. **NDVI:** The Normalized Difference Vegetation Index was calculated for each season using the formula:

   $$\text{NDVI} = \frac{NIR - RED}{NIR + RED} \tag{5.1}$$

   where NDVI represents the calculated index that ranges from -1 to 1, NIR represents the near-infrared band (Sentinel-2 B08) and RED represents the red band (Sentinel-2 B04).

2. **EVI:** The Enhanced Vegetation Index (EVI) was computed using the following equation:

   $$\text{EVI} = G \cdot \frac{NIR - RED}{NIR + C_1 \cdot RED - C_2 \cdot BLUE + L} \tag{5.2}$$

   where EVI represents the calculated index that ranges from -1 to 1, NIR represents the near-infrared band (Sentinel-2 B08), RED represents the red band (Sentinel-2 B04) and BLUE represents the blue band (Sentinel-2 B04). Additionally, G is the gain factor, C_1 and C_2 are the coefficients for atmospheric resistance, and L is the canopy background adjustment factor. In this model, $G = 2.5$, $C_1 = 6$, $C_2 = 7$, and $L = 1$. EVI was calculated to assess whether it provided improved sensitivity to vegetation changes compared to NDVI.

3. **RE-OSAVI:** The Red Edge Optimized Soil Adjusted Vegetation Index (RE-OSAVI) was derived using the formula:

   $$\text{RE-OSAVI} = \frac{(NIR - RED) + 0.16}{(NIR + RED + 0.16)} \tag{5.3}$$

where RE-OSAVI represents the calculated index that ranges from -1 to 1, NIR represents the near-infrared band (Sentinel-2 B08), RED represents the red band (Sentinel-2 B04).

4. **Nitrogen map:** The nitrogen map was constructed using the following formula

$$\mathrm{N}\ (\mathrm{kg/ha}) = \frac{\mathrm{n} \times \mathrm{d} \times \rho_{bulk}\ (\mathrm{g/cm^3})}{10} \tag{5.4}$$

   where **N** represents the calculated nitrogen concetration in [kg/ha], n represents the concentration of nitrogen in [mg/kg], d represents the depth (cm) of the topsoil (assumed to be 30 centimeters in this model), and ρ_{bulk} represents the bulk density of the soil. The nitrogen concentration map acts as measure to compare and verify the nitrogen index.

5. **Nitrogen index** The nitrogen index was derived using the following formula

$$\mathrm{NI} = \mathrm{NDVI} - \text{RE-OSAVI} \tag{5.5}$$

   The nitrogen index is a simple band manipulation pairing the NDVI and RE-OSAVI. Although simple, the operation shows a promising result, as will be the topic of the next chapter.

Comparison of Indices

To assess the performance of EVI and RE-OSAVI relative to NDVI, both indices were plotted against NDVI (see Figure B.1 in the Appendix). The results highlight differences in how each index captures vegetation dynamics. The EVI vs. NDVI plot indicates that for values above zero, EVI provides lower index values compared to NDVI, while for values below zero, EVI results in higher values. This is expected, as EVI is optimized for areas with high chlorophyll content, such as rainforests.

The RE-OSAVI vs. NDVI plot reveals a similar trend, but less pronounced. At small positive and negative values, the differences between RE-OSAVI and NDVI are minimal, whereas for values above 0.3, NDVI consistently registers higher than RE-OSAVI. This is consistent with the design of RE-OSAVI, which is made for monitoring low-density vegetation and bare soil areas visible through the canopy. In Mopani, RE-OSAVI is useful, but primarily in non-commercial zones, as the agricultural fields around Tzaneen contain high-density vegetation.

Overall, the comparison shows that neither EVI nor RE-OSAVI outperformed NDVI in capturing seasonal vegetation dynamics throughout Mopani, because the region is characterized by the contrast between barren lands and commercial agriculture. As result, NDVI is classified to be the most effective index for this study that aims to map this diversity.

A nitrogen concentration map was modelled using data from SoilGrids, providing insights into soil nitrogen levels across the study area. The nitrogen concentration data was then compared with the calculated NDVI, EVI, and RE-OSAVI maps to evaluate correlations between vegetation indices and soil nitrogen levels.

Correlation analysis was conducted by plotting the vegetation indices against the nitrogen values (Figure 5.3), focusing on the relationship between high vegetation index values and nitrogen levels. The findings revealed a positive correlation, indicating that higher vegetation index values corresponded to increased nitrogen content, thus confirming the utility of NDVI as a reliable indicator of soil nutrient status in agricultural lands.

5.1.2 Results

NDVI

The NDVI map highlights the region's ecological diversity (Figure 5.1). The western areas are marked by high values (>0.66), reflecting dense, healthy vegetation throughout the year, typical of well-irrigated regions or areas with continuous plant growth. In contrast, the eastern part, around Phalaborwa, shows much lower NDVI values (0.2–0.45), more variation throughout the seasons indicating sparse vegetation and more arid conditions, as expected in this part of the region.

Of particular interest is the area between Tzaneen and Phalaborwa, which exhibits seasonal variation in NDVI. During spring and summer (September to March), the NDVI averages between 0.55 and 0.6, indicating increased plant growth favoured by rainfall. In autumn and winter, however, NDVI values drop to around 0.2 and 0.15, reflecting the natural die-off of vegetation during the dry season. This region is primarily home to game reserves rather than commercial agriculture, so the NDVI variations represent the natural cycle of growth and die off in wild vegetation, in their natural setting, rather than cultivated commercial crops.

In areas of commercial agriculture, such as the fertile lands around Tzaneen, NDVI would typically remain high throughout the year due to irrigation and crop management, which helps plant growth even in the dry months. For the commercial farms in the west, the NDVI index provides a tool for monitoring vegetation health and density. In managed agricultural systems, a high and stable NDVI indicates well-maintained crops with consistent growth, while declining NDVI could signal water stress, poor soil conditions or pest.

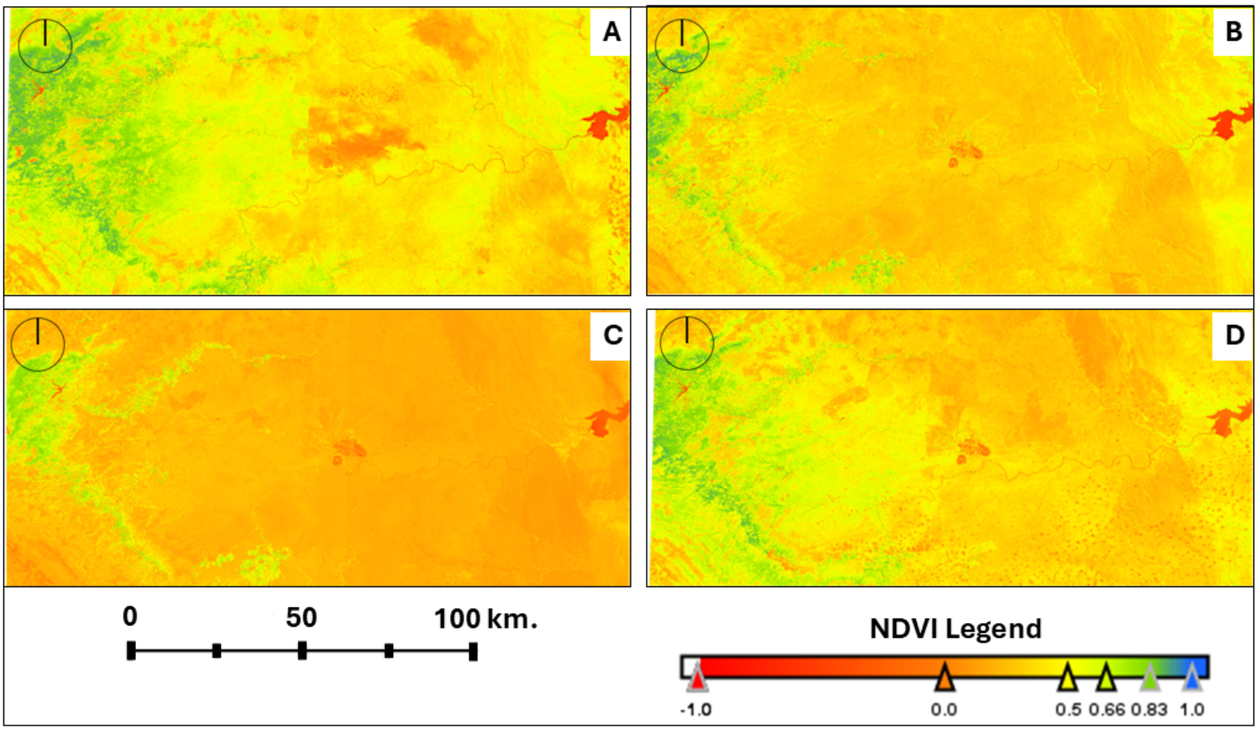


Figure 5.1: NDVI models of the study area. A: March. B: June. C: September. D: December

The seasonal patterns around Tzaneen indicate that natural vegetation dynamics have minimal influence on crop growth in this region. This is illustrated in Figures B.2 and B.3, which provide a two-dimensional and three-dimensional representation of NDVI values across different seasons. The column indices from 0 to 20 correspond to the western part of Mopani, including Tzaneen. Compared to the eastern regions (represented by column indices above 20), Tzaneen exhibits relatively stable NDVI values, with a maximum of 0.8 and a minimum of 0.55 in September—resulting in a NDVI variation of 0.25. In contrast, Phalaborwa (represented by column indices 60 to 80) shows a significant seasonal NDVI fluctuation, with a variation of 0.45. This highlights the contrasting vegetation dynamics between the irrigated agricultural lands of Tzaneen, where crops are consistently managed, and the more arid, less vegetated areas to the east which are dependent on natural dynamics.

Add

Nitrogen map

The nitrogen map, expressed in kilograms per hectare (kg/ha), shows the spatial distribution of nitrogen availability in the soil. The predicted concentrations of nitrogen in the soil are mapped using Equation 4.4 (refer to Figure 5.2).

The color scale ranges from red (low nitrogen levels) to blue-green (higher nitrogen levels). Red to yellow regions indicate low to moderate nitrogen content (38.5 to 75 kg/ha). These regions cover much of the landscape. This suggests that in these regions, nitrogen might be a limiting factor for plant productivity. Green to blue regions indicate areas with higher nitrogen availability (over 100 kg/ha), likely regions with more fertile soils or enriched in nutrients, such as those near rivers, along the outskirts of the Drakensbergen escarpment and in areas of agricultural activity.

A comparison of the NDVI with nitrogen map shows overlap between high NDVI regions (green) and high nitrogen regions (blue-green). Especially along river systems where both healthy vegetation and higher nitrogen content are present. This suggests these areas are characterized by moisture availability and soil fertility.

Similarly, low NDVI regions (orange-red) and low nitrogen regions (yellow-red) show overlap. Areas with lower vegetation health correspond to areas with lower nitrogen content. This indicates that poor vegetation health could be related to both nutrient limitations and potentially other factors like water scarcity. Not all regions show such overlap, for example, some areas may show moderate vegetation health despite low nitrogen levels, indicating that factors other than nitrogen, such as water or other nutrients, may be sustaining vegetation growth.

Let us remember that September exhibits the lowest vegetation activity, dominated by orange and red areas, which indicate sparse vegetation (Figure 5.1. The NDVI in September shows in some areas little resemblance to the nitrogen map, where higher nitrogen content is present. What explains this discrepancy?-it's likely due to seasonal factors, as September marks the end of the growing season, when vegetation begins to die off, leading to decreased biomass and reduced photosynthetic activity, independent of soil nitrogen levels. In contrast, the other NDVI maps (A, B, D) show higher vegetation activity, which corresponds more closely with nitrogen-rich areas, as plants are still actively growing and utilizing available nitrogen during these months.

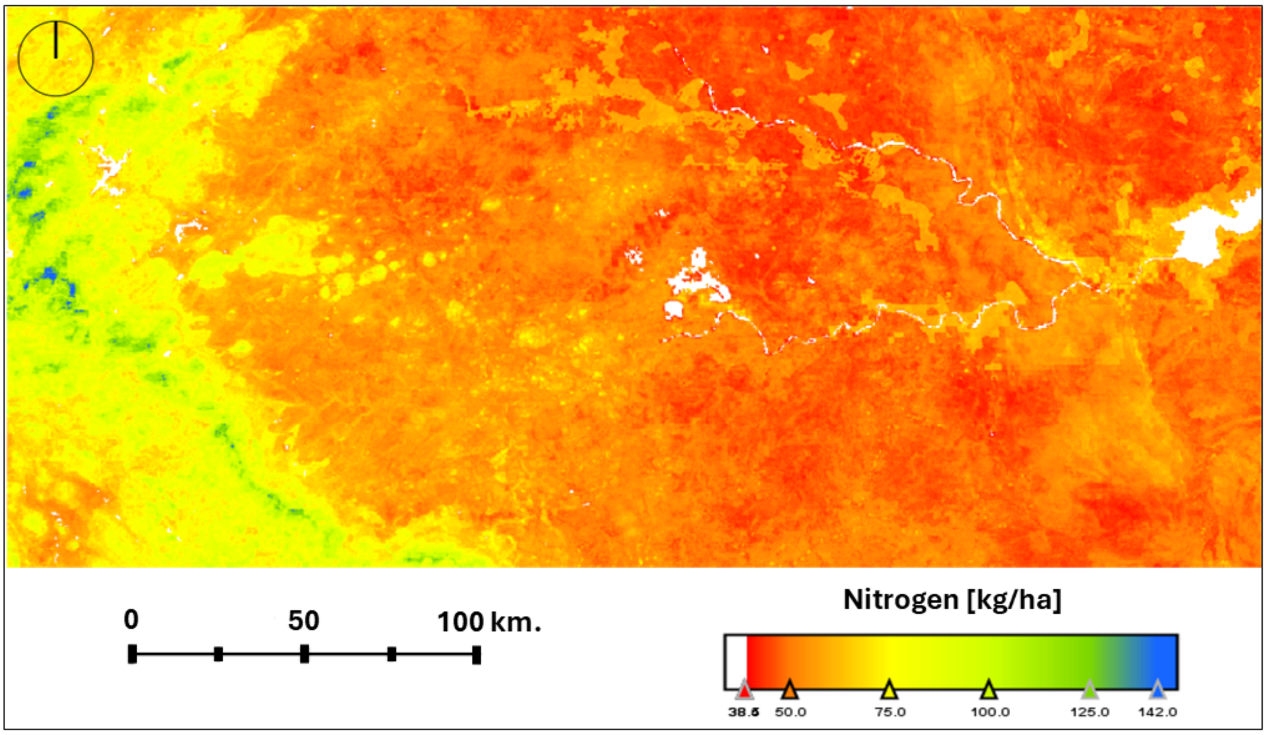


Figure 5.2: Nitrogen map based on data from SoilGrids.org [35]

Nitrogen index: vegetation indices as predictors of nitrogen

Previously the nitrogen concentration map (soil data) was compared with NDVI maps (satellite data) to analyse correlations between soil nitrogen levels and vegetation indices. A correlation analysis shows a positive relationship between higher NDVI values and increased nitrogen content, confirming NDVI's effectiveness as an indicator of soil nutrient status (Figure B.4). However, the NDVI maps alone are not particularly useful in determining the nitrogen presence and levels, as illustrated in Figure 5.3. In fact, areas identified as having relatively high nitrogen levels on the nitrogen map are not clearly distinguished by NDVI.

An additional step is hence required to use the satellite imagery for finding higher levels of nitrogen in the soil. On observation of the correlation plots (Figure B.4), a small but significant discrepancy between the NDVI-Nitrogen plot and the RE-OSAVI-Nitrogen plot is characterised for NDVI values above 0.55 (below 0.55 there's is virtually no discrepancy). To clarify, NDVI values above 0.55 indicate nitrogen levels ranging from 50 to 140 kg/ha, whereas RE-OSAVI values above 0.55 do not correlate with any nitrogen levels, which is attributed to the conservative nature of RE-OSAVI estimation. This discrepancy can be exploited by calculating the difference between the two. By using this approach, the presence of high nitrogen values is inferred, by combining NDVI and RE-OSAVI as predictors for subsurface nitrogen concentrations, as outlined in Equation 4.5. Although this method is not without its limitations, since it only filters out nitrogen levels below 50, it remains significant, as higher nitrogen values typically occur within these higher brackets. Figure 5.3 presents the results of this method. While NDVI proved to be a poor measure for identifying high nitrogen levels (as previously mentioned), the nitrogen index derived from Equation 4.5 demonstrates greater effectiveness and identifies areas of higher nitrogen presence that were previously overlooked by NDVI.

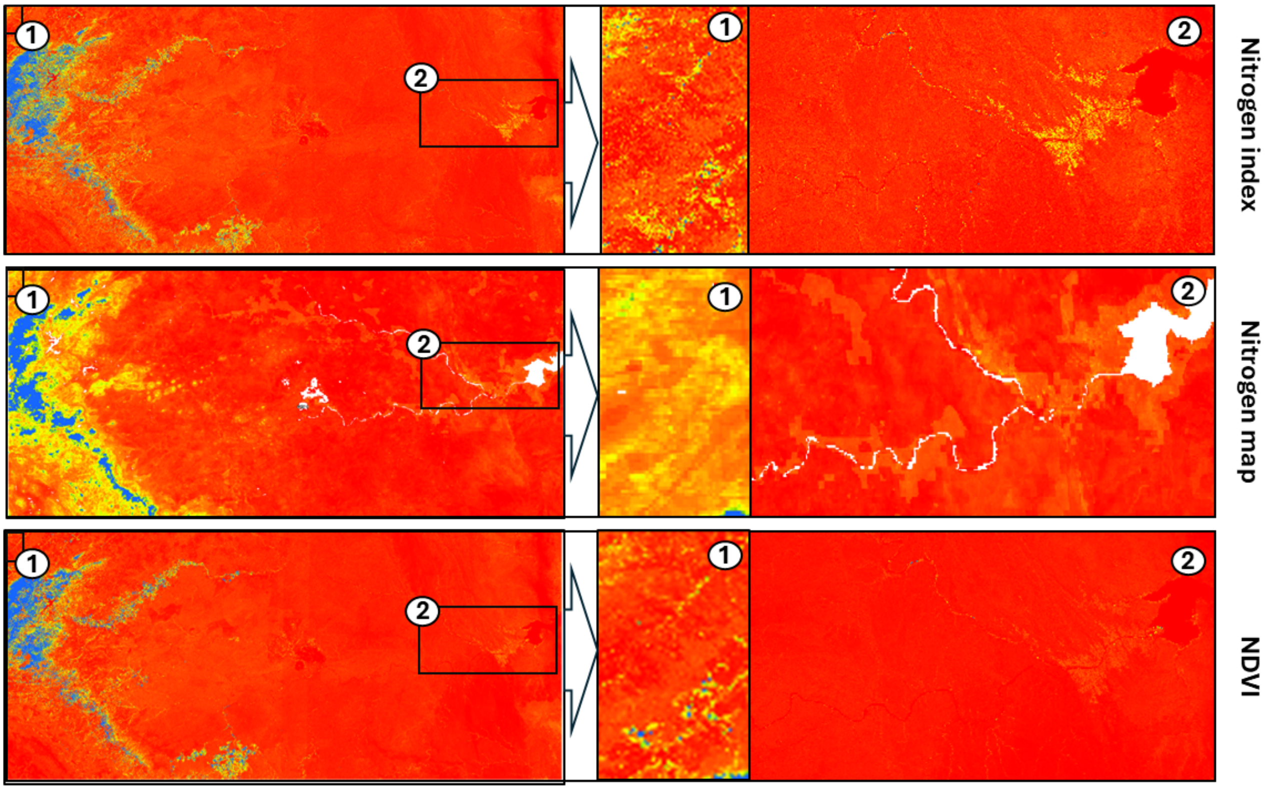


Figure 5.3: Nitrogen map (same data Figure 5.2, nitrogen index (as computed with Equation 5.5 and NDVI map (same data as Figure 5.1) comparison

5.1.3 Synthesis of sensed soil properties and soil maps

The previous paragraph discussed the nitrogen concentrations of soils and also examined the indices, ultimately to determine which lands in Mopani hold potential for commercial farming and which are less suitable, thereby relegated to subsistence farming. The attentive reader has likely already noticed that most nitrogen-rich lands are already cultivated in Mopani. For example, the commercial farms in Tzaneen are identified as suitable for agriculture, which is confirmed by the results indicating they have the highest nitrogen levels. However, the nitrogen map (Figure 5.2) does not fully align with or predict the current agricultural activities; lands with medium concentrations (enough for cultivation of certain crops) are not yet exploited. Why is this the case?

The answer to this question can be formulated by considering what the model is—and what it is not. Many properties, besides the nitrogen content, are not mapped nor remote sensed with satellite imagery. For a proper determination of the soil, though, these properties are necessary. To determine these properties (such as: moisture content, top soil depth and soil organic carbon content) in-situ measurements are required. Ideally, this would be addressed through additional fieldwork. However, given the limited resources, this limitation is tackled by using the soil maps of Mopani. The soil map of Mopani (Figure 5.4) provides indirectly a means to identify these properties and hence the most suitable lands for agricultural development. Essentially the map is straightforward: it delineates the different sorts of soil in the region. By pairing the soil maps with remotely sensed vegetation and nitrogen indices, a speculative conclusion can be reached, identifying 1a) regions with commercial agriculture potential, 1b) regions with no commercial agricultural potential, 2a) regions with subsistence farming potential and 2b) regions with no subsistence farming.

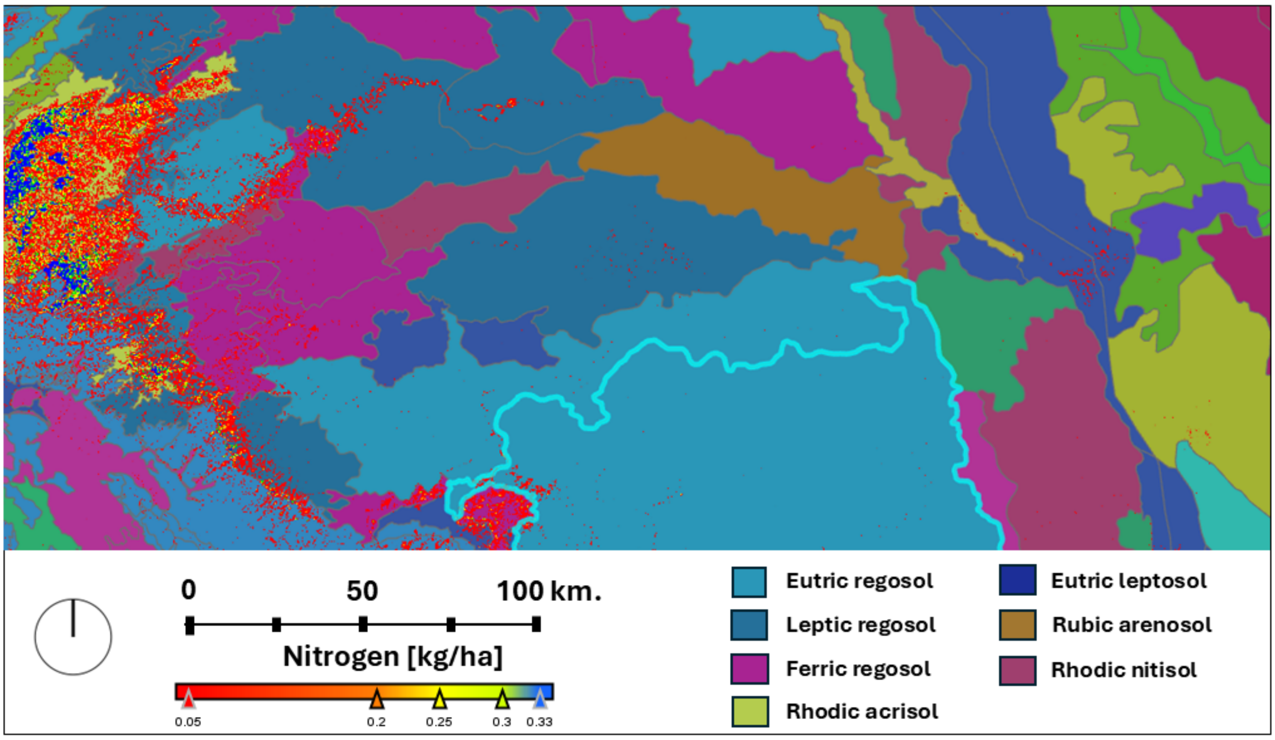


Figure 5.4: Soil map indicating soil types and nitrogen index [37]

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Description of soils

The distribution of the soil types in Fig. 5.4 shows that, generally, the lands closer the Drakensbergen escarpment and rivers streams have higher nitrogen levels. In broad terms the soil transistions from west to east as follows: rhodic acrisol - leptic regosol - ferric regosol / eutric regosol - rhodic nitisol/eutric leptosol - rubic arenosol. The characteristics of the soil types is presented in Table 5.1.

Soil Type	**Topsoil Depth (cm)**	**Theoretical nitrogen Level**	**Moisture Retention**	**Composition**
Rhodic Acrisol	30–40	High	Moderate	High clay content, acidic
Leptic Regosol	<20	Low to Moderate	Very Poor	Rocky, shallow on hard bedrock
Ferric Regosol	20–30	Moderate	Moderate	Clay-enriched
Eutric Regosol	10–20	Low	Poor	Coarse texture, nutrient-poor
Rhodic Nitisol[5]	30–50	Moderate to High	Good	Clay-rich, high fertility
Eutric Leptosol[56]	<20	Very Low	Poor	Well-drained, shallow, rocky
Rubic Arenosol[7]	20–30	Low	Poor	Mostly sand, well-drained

Table 5.1: Summary of Soil Types in Mopani with Key Characteristics. [5]Suffers from waterlogging in flat areas, meaning they drain water insufficiently, leading to water ponds staying on the surface after rainfall, which requires good drainage management. [37]

5.1.4 Discussion

The major limitation of this part of the study is its focus on just one soil property, albeit arguably the most important one. Nonetheless other properties demand attention to ultimately guarantee a complete soil characterization. Hence, in-situ measurement are essential for validating and calibrating the nitrogen index with actual soil samples for nitrogen concentration, ensuring that predictions align with real soil conditions. Additionally, incorporating hydrological data, including rainfall patterns and soil moisture content, improves the soundness of the characterization.

Improving the nitrogen index derived from NDVI and RE-OSAVI can make it more accurate and reliable in estimating soil nitrogen concentrations. One way to improve is by implementing seasonal variations in the nitrogen levels, with separate models developed for different seasons to account for variations in nitrogen uptake and plant growth dynamics, especially during the growing season. Integrating soil properties, including pH, texture, organic matter content, and moisture levels, would provide additional data for nitrogen availability.

5.2 Agricultural future of Mopani

5.2.1 Agricultural potential

Increasing the number of agricultural lands in Mopani appeared to be out of the question. However, the findings of this study suggest otherwise, revealing that the potential of certain lands is greater than prima facie apparent. What are the required resources to actualize the potential of these lands? And which lands require the least resources to realize their potential? These are important questions, because an avocado farm can be established everywhere with sufficient resources, however, this would strain the carrying capacity of the region.

Table 5.2 provides a summary to above questions, by describing each soil type, their suitable agricultural products, and their potential with regard to the carrying capacity in Mopani.

The limited data of this research on food production in Mopani forces us to be humble. Not too many conclusion should be drawn. Nonetheless, some solutions seem viable, especially in regions with ferric regosols and rhodic nitisols. The sections below describe in more detail the possibilites. In the coming chapters, the results gathered here are integrated with the findings on water and energy, ultimately to design a spatial plan for the region.

Soil type	Nitrogen level*	Agriculture [62] [61]	Potential (0-100%)
Rhodic acrisol	High	Maize, sorghum, legumes	50**
Leptic regosol	Low to Moderate (Groot Letaba River)	Grazing, sorghum, legumes	25
Ferric regosol	Moderate	Maize, vegetables, legumes	75
Eutric regosol	Low	Grazing	10
Rhodic nitisol	Low to Moderate	Maize, tea, fruit	75
Eutric leptosol	Very Low	Grazing	0
Rubic arenosol	Low	Grazing, sorghum, peanuts	10

Table 5.2: Summary of Agricultural Potential in Mopani Region. *results from this study. **No available land.

5.2.2 Commercial farming

When it comes to commercial farming, the Mopani region presents both challenges and potential for large-scale agricultural activities. Based on the soil types and their nitrogen levels, certain areas show greater promise for commercial agricultural enterprises, while others remain less suitable for such ventures. The ferric regosol, with moderate nitrogen levels and an agricultural potential of 75%, is of the most viable areas for commercial farming. This soil type supports crops like maize, vegetables, and legumes, which are not only important for local consumption but also have high market demand. Large-scale commercial maize farming could prove profitable in this area, keeping into account that modern farming technologies such as high-efficiency irrigation. Fertilizer use, like everywhere else in Mopani, would play an important role here.

However, commercial farming in Mopani is not without its challenges. For example, the rhodic nitisol, while offering high potential for crops like maize, tea, and fruit (75%), suffers from low to moderate nitrogen levels, which too requires fertilizer input. Over-reliance on chemical fertilizers could lead to long-term soil degradation, and commercial farmers must adopt practices such as the use of organic fertilizers if possible and rotational agriculture, both of which could improve soil structure and nitrogen retention. Moreover, given that Mopani is a semi-arid region, water availability for irrigation is a problem. Implementing water-efficient irrigation systems, such as drip irrigation or rainwater harvesting systems, would be essential for ensuring that crops receive adequate moisture, especially during the dry season.

On less fertile land, such as that with rubic arenosol, only suitable for grazing, commercial farmers perhaps should focus on livestock farming, particularly cattle or goats. Livestock farming could be combined with rotational grazing to prevent land degradation and improve the productivity of the land. In these areas, agrivoltaics could also be an opportunity. By integrating solar panels into livestock farming operations, commercial farmers could generate multiple income streams by selling the solar-generated electricity.

5.2.3 Subsistence farming

Subsistence farming in the Mopani region, defined by small-scale agricultural practices, bears many challenges given the soil type and nitrogen levels across the area. According to the agricultural potential data gathered, the region's varied soils offer mostly constraints for subsistence farmers. For example, the rhodic acrisol areas with Leptic Regosol, particularly along the Groot Letaba River, have low to moderate nitrogen levels, making them suitable for grazing, sorghum, and legumes, with an agricultural potential of 25%. Given the low potential, subsistence farmers would need to use soil enrichment methods such as composting or green manures, which can improve nitrogen availability without relying heavily on commercial fertilizers.

In regions with eutric leptosol, where nitrogen levels are very low, the agricultural potential is rated at 0%, and the land is unsuitable for farming. Such conditions force subsistence farmers to rely heavily on grazing, which might not yield enough for food security. This forces the population to rely on livestock rather than crop farming. Farmers here might adopt a mixed farming system, integrating livestock with small-scale vegetable farming on more fertile land.

Moreover, advancements in agrivoltaics (as explained previously in Chapter 4.3.3), the integration of solar power generation with farming, offers a new potential for subsistence farmers in Mopani. In regions with scarcity of water and land degradation, agrivoltaic systems could help by the dual-use of land for both food production and solar energy harvesting.

Chapter 6

WEF Nexus & Vision

In developing a future vision for Phalaborwa, it became an important challenge to integrate and balance the multiple considerations regarding the WEF aspects, and especially designing under conditions of limited confidence in the available information. This chapter starts with the introduction of a certain methodology to combine spatial design and economic structure options (future visions) constructed from the different possibilities of the current biophysical status (current scenarios). Then, combined with the existing geological / social data and biophysical analysis in the previous chapters, one option among all the future visions will be selected, mapped, and recommended to subsequent researchers for a more refined feasibility study.

6.1 Existing Spatial Structure of Research Area

While researching the possible future of the research area, the existing spatial structure becomes the starting point of the research. The study area can be divided into three areas with different spatial characteristics as listed below and shown in Fig 6.1.

- The Highveld includes the upstream catchment area of the Olifants river. This area is mainly composed of grassland landscapes and is relatively more populated, with better water and agriculture potential.
- The Lowveld, which includes the downstream catchment area of the Olifants River, and most of the Ga-selati river catchment. Most of the important settlements mentioned in this report such as Hoedspruit, Phalaborwa, and Gravelotte are located in Lowveld. However, the Lowveld is considered the lesser populated area within the research area boundary due to its low potential in water and agriculture. KNP is also part of the Lowveld. Lowveld is mostly consisted of a savanna landscape with grass, bushes, Maryland trees, syenite koppies, and termite mounds.
- Eswatini Escarpment, which includes the mountainous area between the Highveld and Lowveld. Due to its richness in groundwater, the area is covered by grass and trees. Several tributaries of the Olifants River and the Ga-selati River are originate in this area as well. Settlements like Tzaneen are located in the hills with agricultural production and timber business. The area also attracts tourists because of its unique geological landscape with ridges, waterfalls, and springs.

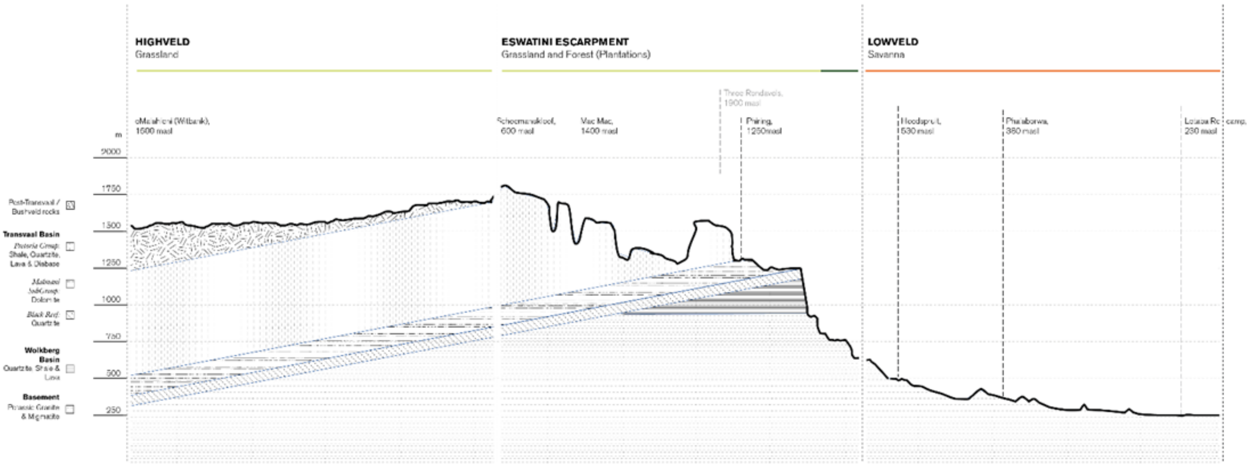


Figure 6.1: The section of the Highveld, the Lowveld and Eswatini Escarpment, made by Isabel Recubenis, geological information from various sources.

The research's vision that purposed the research will be limited to the the surrounding area of Phalaborwa mine (the Lowveld and part of Eswatini Escarpment area). However, there are strong interrelationships between the research area and other parts of the Highveld and Eswatini Escarpment, which makes the discussion of the biophysical features of the the whole section relevant.

6.2 Current Scenarios

6.2.1 Current WEF Nexus

The lack of basic geo-survey data or access to such information leads to difficulties in research. Therefore, the focus on the confidence of the information during the research is as important as the focus on the information itself. In the case of the water, energy, and food components, the study is still limited by the information available and, therefore unable to indicate with complete certainty the spatial distribution and quantity of the potential of these resources. The concept of current scenarios was introduced during the discussion of the WEF nexus. This concept considers the possibility of different current biophysical states existing under uncertain information and becomes the foundation of vision proposal.

From the water perspective, the groundwater and the surface water / precipitation are two essential aspects to look into. However, the lack of concrete borehole records limits the possibility of generating more definitive conclusions on groundwater potential. The study on Malmani Dolomites shows the potential of groundwater in the Escarpment area. However, there is no such certain conclusion for the Lowveld. Therefore, the scenarios of groundwater potential could be divided into three: scarcity of groundwater, unevenly distributed groundwater, and evenly distributed groundwater. The precipitation in the area is rich in the rainy season, however not sufficient throughout the year. Considering the uncertainty of the rainwater use efficiency, the rainwater scenarios can be simplified into adequate and inadequate.

From the energy perspective, small-scale changes and approaches like community-driven initiatives and localized renewable energy installations could have the potentials to make significant impacts. However, considering the lack of utilization of new green energy sources and the reality that most of the energy still comes from external inputs and wood burning. It would be a big challenge to create a new self-sufficient energy source. Compared to water and agriculture, the potential of energy production especially options like solar energy would be less limited by biophysics but more by economics.

From the food (agriculture) perspective, the potential of agriculture is limited by the potential of the soil. Combining with satellite data, soil models, and maps, a preliminary answer is provided to explain the spatial distribution of agriculture potential in Mopani district. The conclusion can be drawn that in the area near Tzaneen and several tributaries of Ga-selati River, there could be potential for agricultural development. However, the conclusion is still drawn from limited data and should be used with caution.

6.2.2 Hydrological Scenarios

The nexus of WEF potential in the research area consists of several biophysical analyses with different confidence shown in Fig 6.2, among all the water potential could be the foundation of the nexus since the water is highly related to agricultural production while energy development is more determined by the business model that could be proposed. Besides, water also has the highest uncertainty of the three elements. Therefore, six current scenarios are introduced based on the possibilities of groundwater and surface water / precipitation potentials, shown in Figs 6.2 and 6.3.

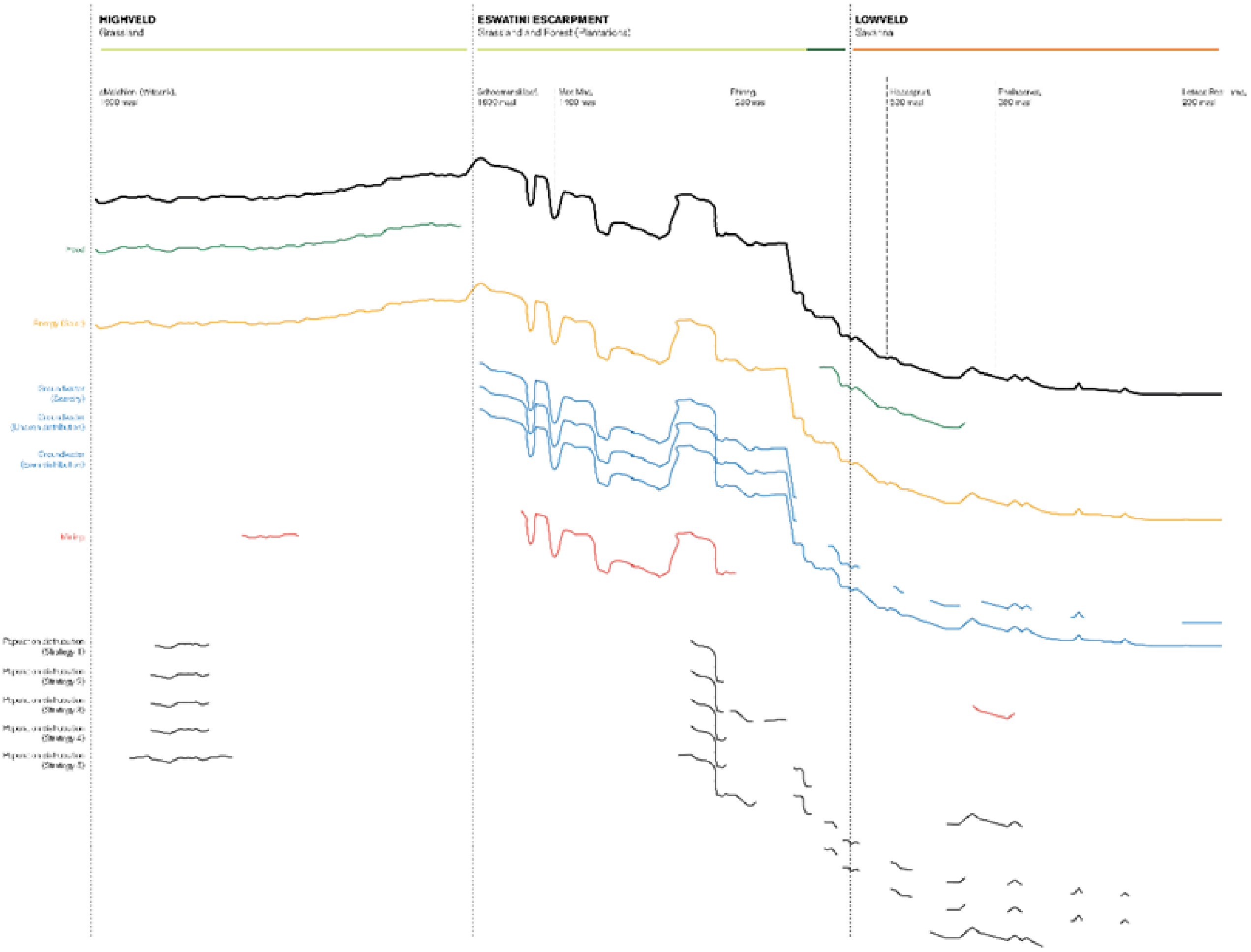


Figure 6.2: The possibilities of WEFM potential based on biophysical analysis, combined with the information in Chapter 3,4 and 5.

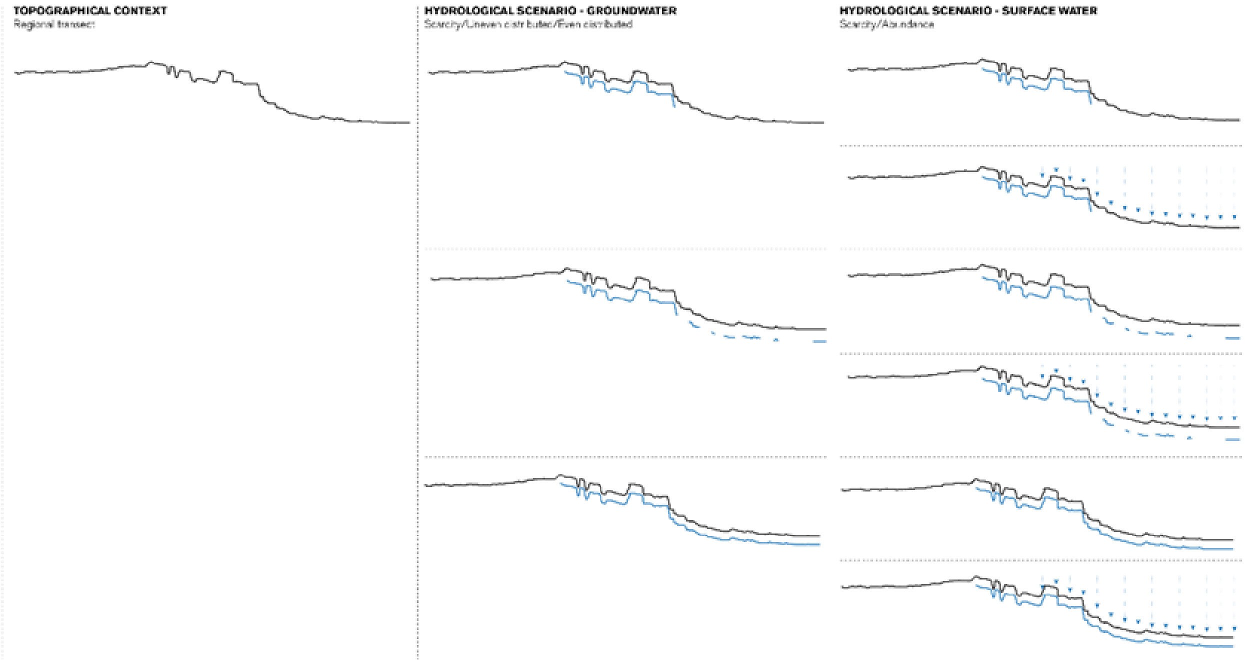


Figure 6.3: Six current scenarios based on hydrological biophysics.

The strategies will be developed based on the six hydrological scenarios. However, it is necessary to mention that agricultural potential maps and the implementation of small-scale energy changes and approaches are still included in the development of the strategies with the awareness of low data confidence. In the future, the possible feasibility studies of not only water scenarios but all WEF potentials mentioned above should be considered for the strategy choosing.

6.3 Strategies

6.3.1 Strategies based on current scenarios

Even though the biophysical studies on the local carrying capacity are limited by the data uncertainty, a mutual understanding of local sustainability could be reached. The carrying capacity of the research area is not enough to support centralized settlement with significant populations like Phalaborwa and Namakgale, especially after the mine closure. Therefore, we developed five strategies considering local carrying capacity, including the possibilities of dispersing the population, relocation, and de-growth, which could be summarized below:

Strategy 1: Infrastructure-dependent centralized population across the Lowveld This is a strategy which the population remaines relatively centralized. However, the population will still be distributed around the areas by expanding existing settlements and creating new settlements in the Lowveld. It will assumably be applied when the potential groundwater and surface water / precipitation are insufficient in this region. The extreme water scenario would limit the local businesses on tourism, energy production, or education. The locations of settlements will be more determined by the infrastructure instead of natural resources and potential.

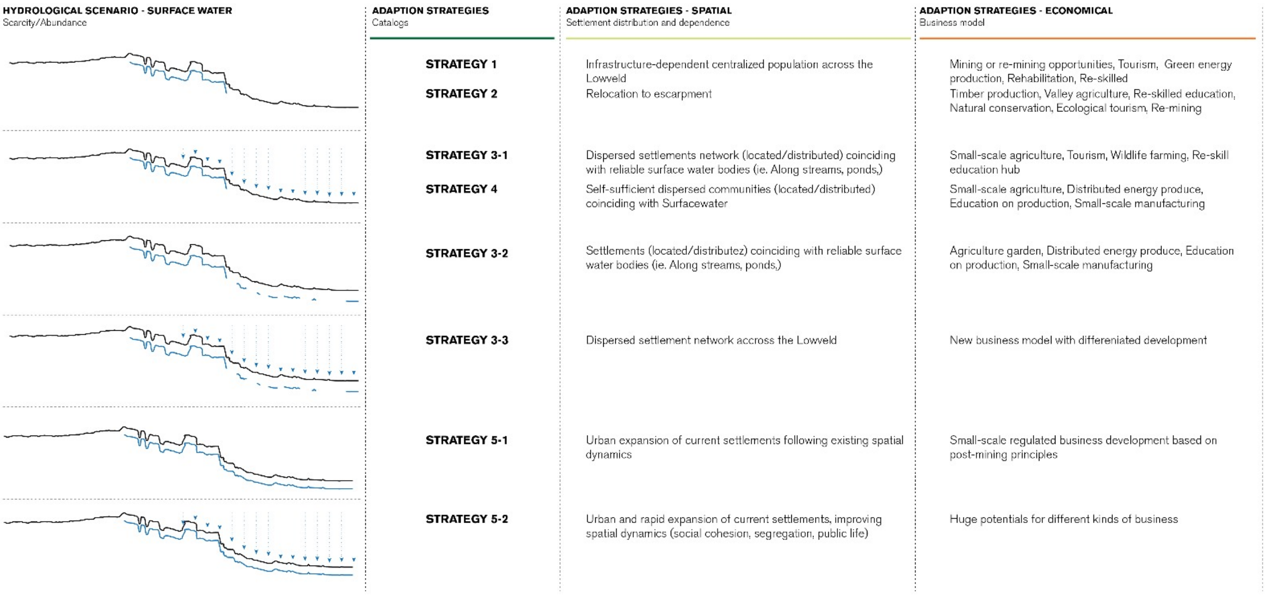
Strategy 2: Relocation to the escarpment This is a strategy that many people who live in Phalaborwa will gradually be encouraged to resettle in the escarpment area, as that area has better water and soil conditions. The new settlement in the escarpment would be able to utilize local groundwater resources to develop timber production and valley agriculture. Ecological tourism would also be an option in the escarpment area. While in the Lowveld, re-skilled education and rehabilitation can be used as environmental compensation as well as a measure to promote relocation. The strategy is supposed to be applied to the scenario of extreme water shortage.

Strategy 3: Dispersed settlement network This is a strategy when people are relocated and dispersed into smaller settlements around several areas with more water resources, soil conditions, or opportunities offered by local infrastructure. Various businesses like small-scale agriculture, tourism, wildlife farming, or dispersed energy production would be possible by combining the specific conditions of each settlement. Trading within the settlement network and trading with outside would also be an important part of this strategy. A network of locally adapted settlements and production networks will be developed in the region. This strategy is more possible to be applied when a limited amount of water resource is available but not adequate.

Strategy 4: Self-sufficient dispersed communities This is a strategy which people are also relocated and dispersed into smaller settlements around available resources like water and cultivatable soil. However, instead of coexisting among one trading network, settlements are focusing more on self-sufficiency. Small-scale agriculture, off-grid energy production, and small-scale manufacturing become essential to local settlements to survive. A small circularity of resources will be constructed in each settlement. This scenario would be applied to the scenarios with limited and evenly distributed water resources, which give opportunities to every settlement to achieve self-sufficiency.

Strategy 5: Urban expansion This is a strategy with the expansion of current settlements following existing spatial dynamics. Regulated development based on consideration of sustainability and carrying capacity will be possible with adequate groundwater resources and rainfall collection. However, this is an extremely optimistic strategy which does not match the current conclusion of local carrying capacity.

It is necessary to mention that the strategy is meant to demonstrate strong and clear images of different possible futures. Therefore, the five strategies are deliberately designed to be an extreme case. However, the strategies can be combined in actual appliances with the consideration of complex realities. Taking into account the different groundwater and surface water scenarios, these five strategies are also differentiated into more detailed sub-strategies, shown in Fig 6.4.



ADAPTION STRATEGIES Catalogs	ADAPTION STRATEGIES - SPATIAL Settlement distribution and dependence	ADAPTION STRATEGIES - ECONOMICAL Business model
STRATEGY 1	Infrastructure-dependent centralized population across the Lowveld	Mining or re-mining opportunities, Tourism, Green energy production, Rehabilitation, Re-skilled
STRATEGY 2	Relocation to escarpment	Timber production, Valley agriculture, Re-skilled education, Natural conservation, Ecological tourism, Re-mining
STRATEGY 3-1	Dispersed settlements network (located/distributed) coinciding with reliable surface water bodies (ie. Along streams, ponds,)	Small-scale agriculture, Tourism, Wildlife farming, Re-skill education hub
STRATEGY 4	Self-sufficient dispersed communities (located/distributed) coinciding with Surfacewater	Small-scale agriculture, Distributed energy produce, Education on production, Small-scale manufacturing
STRATEGY 3-2	Settlements (located/distributez) coinciding with reliable surface water bodies (ie. Along streams, ponds,)	Agriculture garden, Distributed energy produce, Education on production, Small-scale manufacturing
STRATEGY 3-3	Dispersed settlement network accross the Lowveld	New business model with differeniated development
STRATEGY 5-1	Urban expansion of current settlements following existing spatial dynamics	Small-scale regulated business development based on post-mining principles
STRATEGY 5-2	Urban and rapid expansion of current settlements, improving spatial dynamics (social cohesion, segregation, public life)	Huge potentials for different kinds of business

Figure 6.4: Strategies based on hydrological scenarios

The strategies could be used as guidelines for future design and reference for structuring the feasibility analysis, even in the absence of the support of detailed biophysical data.
Besides the spatial distribution of the resource, the quantities of resources are also crucial to consider. Different scenarios require different amounts of water/energy/food. Therefore, a simple comparative analysis of all strategies regarding the requirements of water/energy/agriculture/mining/investment is performed and shown in Fig 6.5.

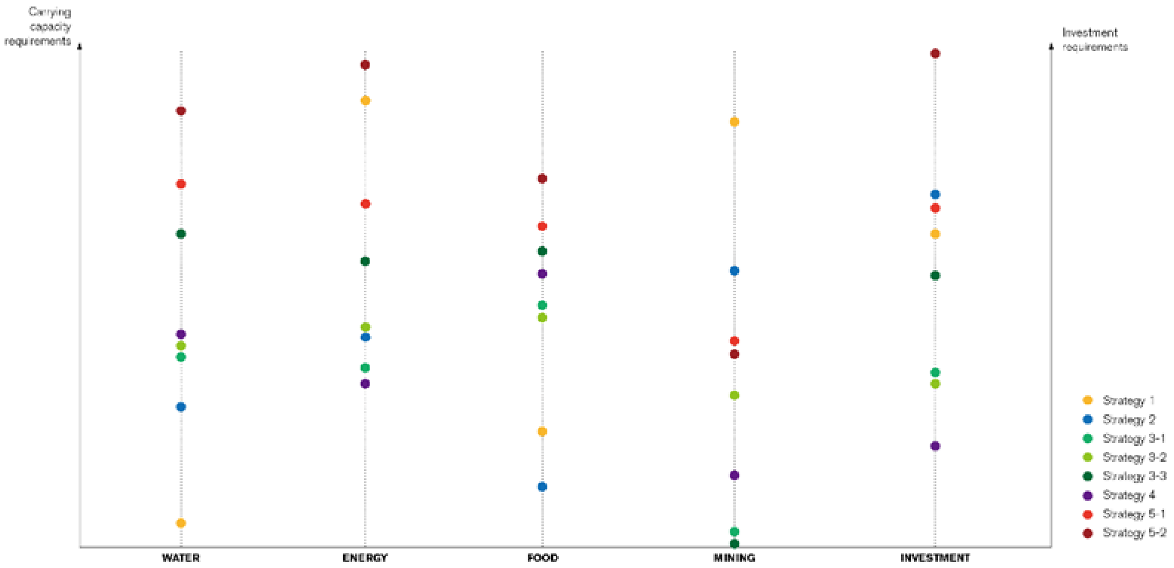


Figure 6.5: Comparative analysis of all strategies regarding the requirements of water/energy/agriculture/mining/investment.

The diagram will function when compared to the potential of the current condition. The comparison can provide guidance for strategy selection and improvement in terms of the amount of resource potential.

6.3.2 Strategy selection based on biophysical analysis

With the analysis and case studies in the last three chapters, one strategy could be selected as the most viable future development possibility. Even if selection of the strategy is based on uncertain data analysis, further deepening of a strategy can still provide inspiration for the implementation of future practical programs. This subsection will incorporate the available hydrological analyses to select a strategy and conduct spatial design further.

As stated in Chapter 3.1, the unregistered boreholes area and the low recharge rate in the Lowveld can be used as support to justify the current lack of groundwater potential. Even though the potential in dolomites regions could also be a possible water source option, the potential of the usage of groundwater sustainably is still doubtful in the Lowveld. On the contrary, the experimental study in Chapter 3.3 proves the rainfall in the wetter months, the potential for rainwater harvesting can not only meet the local demand but also provide surplus water for storage or supplementary use. Rainwater could be an alternative option for providing water for livelihoods sustainably.

Combining the water biophysics information available to us with the knowledge from Fig 6.4, we can tentatively conclude that the scenario with little groundwater potential but precipitation / surface water potential is the one with the highest possibility. Therefore, the research will select strategy 3-1 as the strategy to conduct spatial design further.

The quantity of resources is also considered a crucial aspect in the selection of strategy. Therefore, the comparison research between existing resource potential is based on the analyses in this study and strategy 3-1 resource requirements, shown in Fig 6.6. The confidence of current potential is concluded with the limitation of data. So instead of one certain point on the vertical axis, a range of possibilities is included.

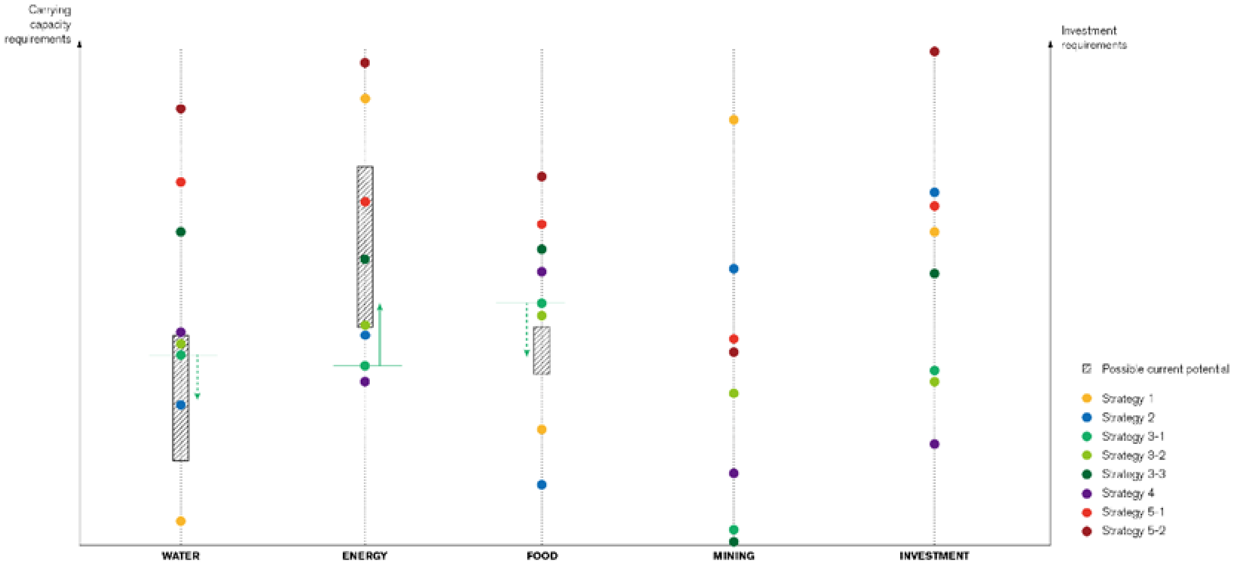


Figure 6.6: Comparative qualitative analysis focusing on strategy 3-1 regarding the requirements of water/energy/agriculture with analyzed current potential.

From the analysis, the amounts of resources requested in strategy 3-1 remain at variance with the most likely reality. The water requirement is higher than the current condition, thus the possibility of bringing in water from outside should still be considered. The potential for local energy production is higher than the base demand in strategy 3-1, leaving the possibility of more possible industries. The potential for agriculture is still below the need for widespread small-scale agriculture as described in strategy 3-1, as the soil with relative agricultural potential is very concentrated in the area of Tzaneen. Agricultural expansion should therefore be carried out more cautiously and confined to areas with good soil and water sources.

6.3.3 Spatial Design based on Strategy 3-1

Based on the proposals of strategy 3-1, a spatial design is formed with several specific strategies based on different spatial segments. Both the basic principles of strategy 3-1 and modifications considering the discussion on the quantity of water/energy/food are included in the conceptualized map of spatial design showin in Fig 6.7.

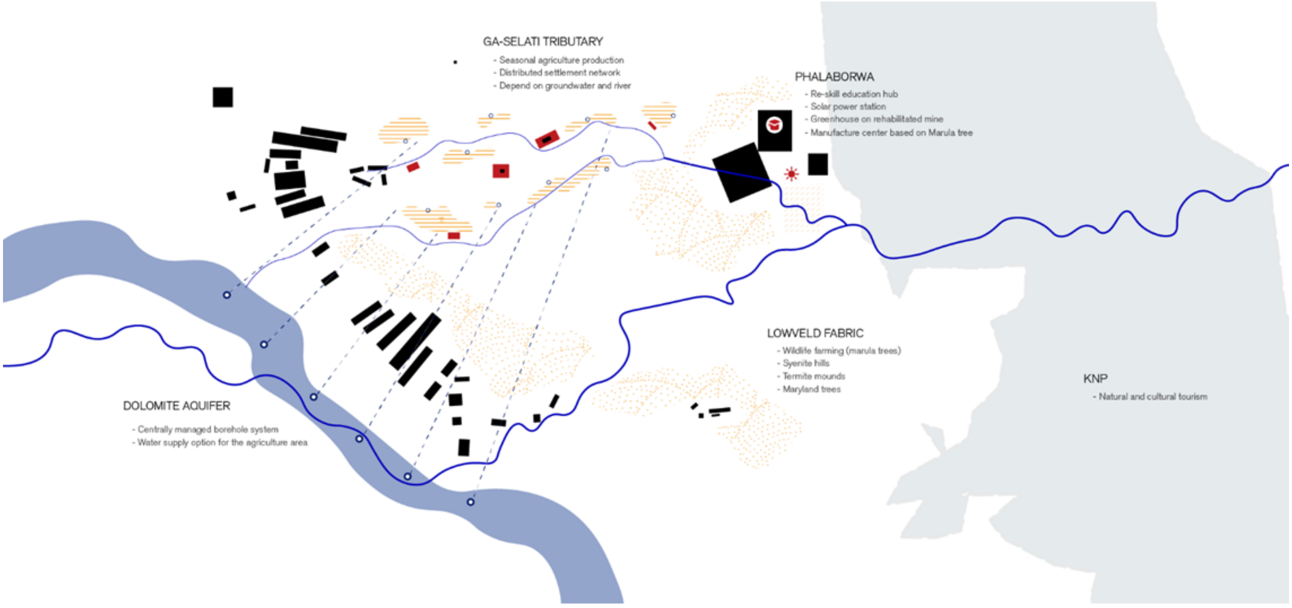


Figure 6.7: Conceptualized spatial design based on strategy 3-1.

The spatial design includes specific strategies listed below:

- Agricultural area in Ga-selati tributary
  As the research argued in the comparative qualitative analysis, existing agricultural potential is insufficient to support widely distributed agricultural development. Soil with agricultural potential is mostly found in the tributary areas of the Ga-selati River. Therefore, the area around the Ga-Selati River was designed as an ideal area to implement the original concept of strategy 3-1, where dispersed settlements will be created or expanded based on existing settlements. The area is also differentiated with potential in groundwater. Some areas have some potential for groundwater extraction, while areas further downstream have no such potential and therefore need to rely entirely on surface water bodies.
  Local precipitation has a very significant seasonal variation, there is also a significant seasonal variation in the amount of water in the river. (Table 3.4) Therefore, a rotational farming system may become an option for local agriculture.

- Dolomite aquifer
  As stated in Chapter 3.1.2, there are more possibilities for greater usage of groundwater in the dolomite regions. Therefore, relatively large-scale and comprehensively managed borehole systems become possible in this area. In this context, sound management practices are essential, as only the proper management of borehole water abstraction can ensure the sustainability of the local aquifer.
  The water extracted in the dolomite regions can be transported to the nearby settlement belt, thereby reducing the dependence of these settlements on surface water bodies. Larger quantities of surface water can flow downstream to agricultural areas, thus indirectly increasing the amount of water available in agricultural areas.

- Phalaborwa
  Even if the strategy suggests an ideal dispersed settlements network, it is unrealistic to expect larger towns such as Phalaborwa to disappear or reduce to the desired size in the short term, thus the research attempts to make some recommendations for the survival of centralized settlements despite the gradual reduction of the Phalaborwa population, in order to provide a buffer program for the long process of reaching the final vision.

  In Phalaborwa, energy production such as solar panel station could be possible with the investment of PMC or Foskor. Greenhouse could also be integrated into the plan considering local energy production potential. Reprocessing of agricultural products contributes to a more integrated industrial chain model locally. The marula tree-based agro-processing model can bring local economic benefits without overusing the local agricultural potential. In addition, the conversion of the college in Phalaborwa into re-skill education will help to provide human resources for the transformation of the local industrial model.

- Lowveld fabric
  The Lowveld fabric represents the vast natural areas without the influence of urbanization and commercial agricultural development, including several game reserves. The natural landscape of this area remains relatively well preserved. Unique landscape elements like Syenite hills, Termite mounds and Maryland trees build up the characteristic savanna landscape of the Phalaborwa region. However, this area is also constrained by low water and agricultural potential.
  The theme of this area is to protect and limit overdevelopment. However, plants such as the marula tree, which originally existed in local nature and have economic value, are also worthwhile as part of agricultural activities. The introduction of concepts like wildlife farming can bring more economic income to the local area without compromising sustainability.

- KNP
  The Kruger National Park is also included in the study as an important part of Lowveld. However, the Kruger National Park also suffers from over-utilization of resources. The number of animals present in the park far exceeds its carrying capacity, and the park supports these animals by extracting groundwater.
  It should not be overlooked that the value of the Kruger National Park is also reflected in its cultural heritage. For example, there is tourism value in the traditional ironworks. This could be a possible alternative to the current unsustainable development of tourism.

By combining the five strategies, a more detailed spatial design can be presented on the map shown in Fig 6.8.

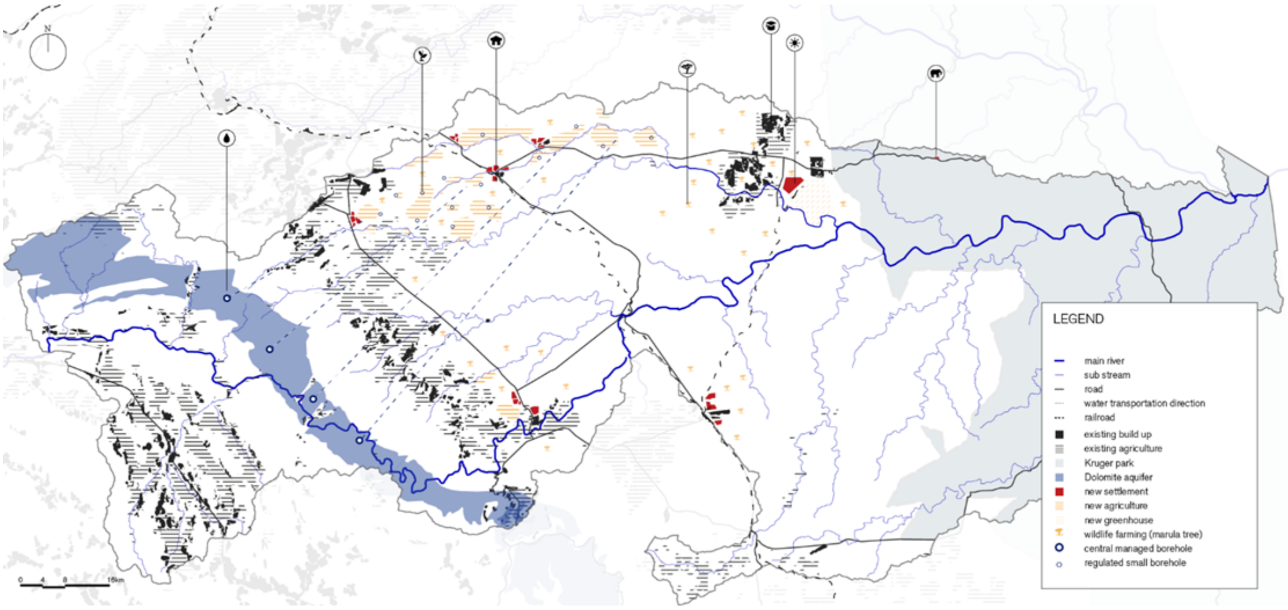


Figure 6.8: Spatial plan based on strategy 3-1, geological data from various sources.

6.3.4 Preliminary feasibility discussion based on strategy 3-1

Based on the underlying spatial design, the included strategies can be discussed in terms of feasibility. However, as stated several times in previous discussions, the conclusions of this section are still constructed on a considerable degree of uncertainty from the available data. The section aims to discuss the possible direction of the feasibility study, thus providing advice for future studies to fill research gaps from design end.

The economics feasibility is one aspect to focus. From Figure 6.6, strategy 3-1 has a relatively low dependence on investment among all strategies. However, it also has relatively little access to outside investment in the post-mining era. As a result, analyses of high investment-requirement strategies will be of great value in the study of the area.

Population migration and settlement development require more initial facilitative investment to encourage people to move to unfamiliar living environments. In addition to this, investment in the infrastructure itself should also be considered. The establishment of an integrated managed groundwater abstraction project in the dolomite area is also likely to have a significant impact on the initial outside investment. In addition to the initial investment, ongoing maintenance work is required at the solar panel station as well as the greenhouse.

However, the abundance of solar resources makes the construction of solar power plants valuable to the local mining industry as well. It is possible to use solar power to replace part of the mining industry's electricity needs, thereby directing PMC or Foskor to invest in the construction of solar power plants. This will still benefit local settlements, as solar power plants can be converted to civilian use in the post-mining era. This model also gives us insights on obtaining investments from mining companies. However, the search for common interests between settlements and mining companies still needs to be researched and discussed.

Another essential discussion is the time needed for the strategy implementation. Processes such as population movements can take decades. And the phased process design is equally important as the final vision.

Fortunately, mining will remained viable in the region for quite some time if PMC continues extending their life of mine. The continuation of the mining industry can provide us with the opportunity to shift towards the final vision. However, this creates new contradictions. Do these shifts towards an ultimate vision conflict with the mining industry? A complete development time study can help local development go towards the final vision.

In any case, the most important thing is to start planning for the post-mining era before the mining industry ends. Mining continues to be of great value in providing financial support for the necessary transformation. These possibilities will disappear completely when mining ends.

Chapter 7

Discussion & Recommendations

This project adopts a holistic, nexus-based approach to address the region's challenges from multiple disciplinary perspectives, providing a comprehensive strategy for sustainable development in Phalaborwa. While this approach strengthens the report, it also reveals areas that require further exploration and improvement. This chapter will discuss key insights beyond the proposed strategy 3-1 and provide recommendations to guide future initiatives.

The varied scales used by each discipline raise questions about a unified boundary framework to better integrate WEF interactions. Each study area was tailored to the specific focus of its discipline, yet it remains unclear whether the interactions among water, energy, and food systems would benefit from a unified boundary framework. Addressing this question could be crucial for shaping strategies toward a sustainable, post-extractive future in the region. Water emerged as the initial bottleneck, unsurprising given the semi-arid to arid climate, guiding the spatial plan to align with the B7 catchment boundaries. However, we might ask whether these boundaries restrict the potential benefits that a broader perspective could offer. While the report acknowledges that the region relies on imports for its water, energy, and food needs, it mainly seeks solutions within its current boundaries. This constraint-based approach deserves further scrutiny before it is adopted in future studies, as it may limit the proposed scenario's relevance by focusing too narrowly on a specific spatial scale.

Another discussion point is the need for quantitative, holistic, and multidisciplinary data to support the study's objectives fully. The lack of high-quality data resulted in decision-making based on a primarily semi-quantitative or qualitative assessment, such as the targeting of productive soils for agriculture and the recommendation of groundwater production in the escarpment. Therefore, follow-up studies are critical to ensure the viability of the proposed scenarios by means of more detailed and data-driven research. Recognizing the inherent difficulty in obtaining high-quality data for complex interdependencies, this report nonetheless establishes a valuable biophysical baseline for the region and highlights locations and methods with the greatest potential for future opportunity.

While many perspectives are represented, the complexity of each discipline and their interdependencies remains challenging. Although the report adopts a WEF-nexus approach to address spatial issues, additional factors such as cultural heritage, social equity, and economic viability warrant consideration to achieve a truly comprehensive view. Research in these areas would deepen the analysis and broaden the report's relevance. This is exemplified by the proposed solution of solar panels. The proposal to replace coal with solar panels in Phalaborwa is an environmentally positive step, offering a sustainable and cleaner energy source. Solar energy could reduce greenhouse gas emissions and align the area with global sustainability goals. However, the high capital expenditure of a solar array poses a major economic challenge, particularly in a region where much of the population lives in poverty, making external funding sources likely essential to finance the project. This raises concerns about the practicality of the proposed solutions. Solar panels are highlighted here, but the argument is valid across the board. For example rainwater harvesting, if done correctly and on a large scale to maximize productivity, will also require tremendous planning and likely high costs.

Further consideration points are the issues with adequate governance and environmental factors. The energy chapter already stressed the incredible dependence on the ruling government, the need for its proper functioning, and the harm of corruption. To ensure a truly positive outcome for the region, the need for a trustworthy government must be a given. Furthermore, even though the report underlines the inherent environmental problems in the region and that they should be addressed immediately, clear solutions are not presented. Pollution caused by mining activities at the PIC, and methods to reduce eutrophication levels in water systems have not been proposed and are likely costly without a high return on investment. Improvements in this department could be achieved by creating economic incentives to tackle these problems. As an example, a recent and first study on mining wastes revalorization in the PIC showed the potential of some of these tailings [33]: *"Therefore, the current content of REO in East and Selati tailings are estimated to be above 4 and 6 Mt., respectively. The most profitable rare earths in PIC wastes are the oxides of Nd, Tb, Dy and Pr (92% of net value). According to easily extractable and total content of REO, East tailing is valued between 28 and 127 billion dollars; while Selati tailing value range between 100 and 130 billion dollars, respectively."*. Incentivizing the reprocessing of these enormous and toxic waste piles provides the opportunity for governmental bodies to correct in-hindsight unsustainable choices that were made in the previous century when mining commenced. This is and will not be easy, and should be encouraged and supported by national governance. The necessity of a clean and healthy ecosystem is incredibly vital for the community and future industries, such as ecotourism.

The results of this report offers insights into the carrying capacity of WEF-systems in semi-arid rural regions and its key drivers, extending beyond the specific challenges of the Phalaborwa area. While water scarcity emerges as the primary issue, one should carefully consider that the dependencies and drivers within WEF-systems can vary considerably. These variations often reflect unique environmental factors, such as soil fertility or solar irradiation, which may alter the region's resource dynamics and, consequently, its approach to transitioning from extractive to non-extractive futures. An infamous example of a complex WEF-system in semi-arid region is Central Valley, USA. Here high soil fertility, access to abundant energy and subsequent high agricultural productivity caused over-reliance on groundwater. Consequently this overabstraction caused severe problems, like subsidence seen in figure 7.1. Central Valley's example demonstrates that energy infrastructure and soil fertility can both act as support and stressor on WEF-systems in semi-arid regions, and that great care must be taken to maintain an equilibrium of these vulnerable WEF-systems or one can run the risk of worsening the situation at hand.

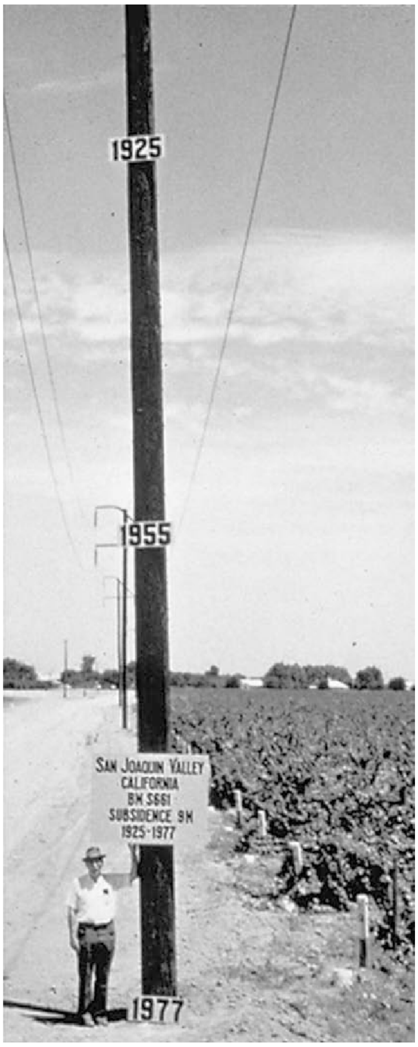


Figure 7.1: Famous picture of Joseph Poland, USGS scientist, showing 9 m of subsidence in 52 years due to overabstraction.

7.1 Future research and further steps

To advance the goals outlined in this report, and develop further support for the proposed strategy, continued research and further actions are vital in refining knowledge and expanding capacities within the WEF sectors. Recommendations were made in the three respective WEF sectors and are believed to support a strong foundation for a sustainable and non-extractive future of the region. The following qualitative timeline outlines potential strategic steps for each sector to prioritize research and action, ensuring steady and realistic progress.

Water

Updating and centralizing water knowledge and supply is a priority, as reliable data on water resources needs to be accessible to all stakeholders. Building on the AWARD project, which served as the basis for much of the water chapter's content, initial efforts should focus on establishing a centralized water data platform. This would enhance data accessibility and transparency, providing a foundation for testing rainwater harvesting feasibility and urban storage solutions in select areas. As data and insights are gathered, storage infrastructure expansion and water consumption studies should be conducted to understand distribution more accurately across different scales. This process will allow strategies to be refined with feedback from communities, ensuring that water distribution supports the unique requirements of each WEF sector. Over time, these efforts can evolve into a fully integrated water management strategy across the region, balancing water resources with the energy and food sectors and promoting equitable access based on early research outcomes.

Energy

Given the region's rich solar potential, future research should emphasize effective solar energy utilization through flexible, community-oriented strategies. Starting with feasibility studies for community-scale solar projects will help identify optimal configurations suited to local needs. Community involvement in these projects, such as through pilot programs, will help build awareness and provide immediate feedback on grid reliability and performance. As data and support grow, expanding these pilot projects will be essential for wider adoption, along with seeking green funding sources to modernize grid infrastructure. This infrastructure is critical for accommodating increased solar energy inputs, which can be gradually scaled to support a decentralized, reliable energy supply. By maintaining adaptability and building on lessons learned, the energy sector can shift sustainably toward renewable sources that align with both the community's current and future needs.

Food

Identifying suitable areas for agriculture will require further site assessments, taking additional factors like soil moisture, phosphate content, and nitrogen indices into account. This initial assessment will provide a clear picture of agricultural suitability and guide early interventions for soil management and crop planning. Small-scale pilot projects should be initiated across select areas to test various crop and cultivation methods, and to monitor how these methods impact soil health and productivity over time. As initial projects progress, local farmers and stakeholders can be involved in refining soil and crop management techniques, benefiting from data-informed best practices. Eventually, findings from these projects will contribute to a comprehensive agricultural strategy that ensures long-term soil health, productivity, and food security. Community education programs and hands-on workshops will further support local farmers in adopting sustainable practices, creating a lasting impact on the agricultural sector.

In summary, to advance the strategy proposed in this report, each WEF sector requires targeted actions: from updating data systems and modernizing infrastructure to implementing pilot projects for energy and agricultural development. Emphasizing an integrated approach will be essential as these sectors evolve together, and attention to local governance and community needs will further support a sustainable future for Phalaborwa. These next steps form a critical foundation for refining and realizing the transition to a resilient, non-extractive economy.

Chapter 8

Conclusion

In this chapter, answers to all the sub-questions will be provided. Combining all the discussion points that were covered in previous chapters. Consequently, the main research question will be answered with a mutual conclusion of all the sub-questions.

8.1 Research sub-questions

What is the carrying capacity of WEF systems in semi-arid rural regions?
This question has been explained in chapters 3/4/5 with analysis indicating the contributions and limitations of this research. In semi-arid rural regions, the carrying capacity of Water-Energy-Food (WEF) systems is focused on the interplay of natural resources and sustainable management practices. Our project highlights key factors impacting these systems.

The recharge rates of groundwater and the presence of dolomite have a big impact on water availability. Seasonal rainfall and efficient water collection are essential to keep a stable water supply. These factors highlight the need for better water conservation methods and infrastructure to use water efficiently.

Nutrient-rich soil and available water capacity are crucial for agricultural productivity. In semi-arid areas, it's important to focus on soil health and water management to ensure sustainable food production. Using practices that improve soil nutrients and water retention will help agricultural systems withstand climate changes.

Using solar energy can meet the energy needs of agriculture and communities in these regions. Solar energy can greatly reduce dependence on traditional energy sources, promote sustainability, and improve the overall efficiency of WEF systems.

By integrating these strategies, semi-arid rural regions can enhance their WEF systems' carrying capacity, ensuring a stable and secure future.

However, the carrying capacity, which was concluded in this study, is still limited by insufficient available data. Therefore, more detailed analyses of carrying capacity should be included in further studies. Subsequent studies in this paper are still based on currently available biophysical information, however, including a full understanding of the insufficient confidence of the information and data.

What WEF-based infrastructures/technics/relational spaces are key to this transition and how?
Several already existing infrastructures/technics/relational spaces regarding water/energy/food are analyzed in the research. However, it is also important to consider the interrelationship between these elements.
For water aspect, boreholes are one of the key elements related to the sustainability of water. However, more potential could be found in dolomite regions. Seasonal river and rainfall changes also influence local water potential. Seasonally varying amounts of available surface water provide conditions for crop rotation agriculture. Besides, flat roof also provides rainwater collection space therefore making the rainfall experiment possible.
For the energy aspect, the possibility of solar energy is researched in the report. Several case studies with the demonstration of several new technics like mini grid, solar geysers and agrovoltaics have been discussed. The introduction of solar energy and related infrastructure could be considered as small changes to help transfer Phalaborwa from using outside electricity sources and wood burning into green energy.

For the food perspective, boreholes would also be important elements since food production is highly related to the water. Besides, soil condition is considered as the key factor to analyze the local carrying capacity of agricultural production. Greenhouse, rotation farming and wildlife farming are discussed in the vision chapter as possible future options of agricultural production.

It is also necessary to mention the elements mentioned above is categorized in water/energy/food, however it is also important to consider them as a interrelated nexus. The nexus of water/energy/food is also included in the vision chapter where we elaborate the how these three aspects relate to each other and forming a complete space design.

How is this transition affecting (what qualities and for who/what) semi-arid rural regions?
Even the study takes full account of the confidence level of the information and remains open to the possibility of the current situation, the basic mutual understanding that can be reached is that the existing population far exceeds the local carrying capacity. Consequently, the population and resource redistribution would more or less be embedded in different strategies. Smaller and more dispersed settlement networks are more likely to be the future spatial structure of the region.
This is because the carrying capacity of the current situation cannot be fully determined with the currently available data. The study takes different current scenarios and thus proposes eight different possible strategies. However, the diversification of production modes is another mutual understanding. Multiple water/energy/food-based economic models exist for the post-mining era, based on different resource types and forms of spatial distribution. Diversified economic models can also increase local resilience.
In this diversified post-mining economic model, it is necessary to integrate the water/energy/food potential and to achieve sustainable development on all three aspects. Combined with the preliminary conclusion of carrying capacity, local sustainability implies a much smaller and more cautious pattern of development. Centralized industrial systems such as mining, on the other hand, can hardly exist in the context of sustainable development.

8.2 Main Research Question

What are the characteristics of a decision-making process (data, workflow, goals) in which the local carrying capacity of WEF systems is the starting point in transitioning a semi-arid rural region from extraction to non-extraction territory?
The limitations of available information were a constant topic of discussion throughout the research process. The standard processes from biophysical studies to feasibility studies, and to design would be influenced by insufficient geographic data. Our mutual understanding is that our research could be the foundation of future feasibility studies from both the perspective of biophysical analysis and spatial design.

From the uncertain carrying capacity analysis on water/energy/food, current scenarios could represent the generalization of the possibility of the current situation. And strategies are proposed based on different scenarios, with several mutual principles like population/resource distribution and diversification of production models. The gaps indicated in the biophysical studies and the possibilities of different strategies could the guideline for future feasibility studies.

Chapter 9

Reflection

Reflecting on our multidisciplinary project, we have gained significant insights and learned valuable lessons by integrating the fields of architecture (urban design and landscape architecture) and mining engineering. Our efforts aimed to implement the Water-Energy-Food (WEF) Nexus approach in Phalaborwa, focusing on creating a sustainable scenario for the post-extraction landscape in this rural area. This chapter dives deeper into the personal experiences of the group members.

9.1 WEF Nexusing

Working on the WEF Nexus project in Phalaborwa was an eye-opener, both in terms of the challenges of sustainable development and the dynamics within our own team. At the start, each of us naturally gravitated toward our individual areas of appointed expertise. In those early stages, we were essentially working in parallel rather than together, each tackling a different aspect of the project without a real sense of integration.

It wasn't until much later, as we approached the final stages, that we came together to truly engage in "nexusing" and think holistically about the intersections between water, energy, and food security. Looking back, it's clear that if we had established this interdisciplinary collaboration earlier, our project might have taken a different direction, perhaps with more cohesive and actionable outcomes.

Yet, we wonder if it would have been possible to have those effective discussions earlier on, given our initial lack of knowledge and experience with the WEF Nexus approach. In hindsight, the process highlighted just how critical it is not only to have a collaborative mindset but also to equip ourselves with a foundational understanding of each other's fields from the beginning. This experience has underscored for us the importance of interdisciplinary learning. Not just for the sake of a project outcome, but for building resilient systems that genuinely address the interconnected challenges of spatial design with a WEF approach.

9.2 Field trip to Phalaborwa, Limpopo

Our field trip to Phalaborwa presented us with invaluable insights into the intricate social, cultural, and environmental landscape of the region. Coming into the community as outsiders tasked with envisioning solutions for a sustainable future, we initially felt a sense of moral conflict. It felt presumptuous, as if our position overlooked the years of work already invested by local, regional, and national stakeholders. However, this perspective began to evolve as we spent time with the local communities and experienced their welcoming hospitality. For example, our visit to Angel's Spaza Shop wasn't just about tasting local cuisine; Angel's warmth and openness in sharing her experiences gave us a profound sense of connection to the community. Moments like these helped us see Phalaborwa beyond mere statistics and data points. Similarly, our time at Thomo Heritage Park, where three local men proudly demonstrated their traditions, highlighted the region's rich cultural heritage and deep-rooted pride. Yet, these moments also underscored an important realization: there is a significant gap in awareness among the community about sustainable practices and the finite nature of their local resources, such as mineral abundance.

While our schedule primarily emphasized cultural engagement, which helped us better understand the community's values and perspectives, it did leave less time for discussions on technical engineering endeavors. This emphasis on cultural immersion gave us a fuller appreciation of the social context within which any future engineering or environmental initiatives would unfold. Although we didn't dive deeply into technical matters, this experience reinforced the importance of grounding technical solutions in the cultural realities and priorities of the communities they aim to serve.

Our exposure to the mining industry, particularly through our limited and arguably censored conversation with the environmental superintendent of PMC, underscored the complexity of Phalaborwa's post-extraction future. Having more specific data from the mining company would enable a clearer view of the region's ecological and economic landscape and help inform plans for mitigating environmental damage.

Ultimately, this experience highlighted the importance of respectful collaboration, where insights from both local and external perspectives can intersect to form a more holistic approach. Though we started with some uncertainty, our time in Phalaborwa showed us that fresh viewpoints can complement local expertise. Balancing both perspectives may be key to finding sustainable, culturally sensitive solutions that honor Phalaborwa's rich heritage while addressing its modern challenges.

9.3 MDP

One of the most rewarding aspects of our project was the interdisciplinary collaboration that brought together architecture, urban design, landscape architecture, and mining engineering. With three of the four team members persuing a degree in mining engineering, we faced the challenge of diving into water, energy, and food systems. These areas lay far outside our usual expertise. This meant each of us had to become "experts" in new fields while moving the project forward, an intense but rewarding learning curve.

We also encountered contrasting problem-solving approaches: the engineering side was practical, aiming for efficient, measurable solutions grounded in existing technologies. Meanwhile, the architecture team embraced a visionary, conceptual approach focused on long-term impact and community inspiration. This mix of practical and creative thinking added valuable depth to our work, combining immediate feasibility with aspirational goals.

In the end, the MDP pushed us out of our comfort zones and underscored the power of blending disciplines. It taught us that by embracing diverse perspectives, we can develop solutions that are both realistic and forward-looking. We learned an approach that will stick with us and likely add great value to future projects.

Bibliography

[1] FAO Water Productivity Open access Portal (WaPOR). Actual evapotranspiration and interception (national - annual - 100m). Data retrieved from WaPOR database, May 2023.

[2] Statistics South Africa. Census 2011: Municipalities in south africa, 2011.

[3] Statistics South Africa. Census dissemination, 2024.

[4] Olanike Olowoiya Aladenola and Omotayo B. Adeboye. Assessing the potential for rainwater harvesting. *Water Resources Management*, 24(10):2129–2137, 2010.

[5] AWARD. Capacity development for water demand and water conservation management: Ba-phalaborwa municipality, 2018.

[6] Ba-Phalaborwa Municipality. Ba-phalaborwa municipality integrated development plan (idp) 2024-2025, 2024.

[7] BA-PHALABORWA SUSTAINABLE COMMUNITIES PROGRAM 2014-2019. BA-PHALABORWA LOCAL ECONOMIC DEVELOPMENT STRATEGY. Technical report, Ba-Phalaborwa Municipality, Phalaborwa, South Africa, 2019.

[8] BBC News. South africa's power crisis: Why the lights keep going out. *BBC News*, 2023.

[9] J. Beumer and S. Mallory. Development of a reconciliation strategy for the olifants river water supply system (wp 10197): Water requirements and water resources report, December 2011.

[10] Chief Directorate: National Geospatial Information (CDNGI). Aerial photographs of phalaborwa study area. Aerial photographs obtained from the Chief Directorate: National Geospatial Information (CDNGI), 2018. Data accessed from https://surfdrive.surf.nl/files/index.php/s/V3i4hduH6uPRsen?path=

[11] Directorate Water Resource Classification. Classification of significant water resources in the olifants water management area (wma 4): Ecological water requirements report. Technical Report RD-M/WMA04/00/CON/CLA/0511, Department of Water Affairs, South Africa, September 2011.

[12] European Commission, Joint Research Centre, A Toreti, D Bavera, J Acosta Navarro, L Acquafresca, C Asega, P Barbosa, F Collivignarelli, W Combere, A De Jager, G Fioravanti, S Grimaldi, A Hrast Essenfelder, H Kabengela, P Kamsu Tamo, K Lawal, D Magni, M Mazzeschi, N McCormick, M Meroni, R Nkurunziza, G Nshimirimana, F Rembold, and P Salamon. *Drought in Southern Africa – April 2024*. Publications Office of the European Union, 2024.

[13] Palabora Mining Company. Water management fact sheet, 2018. Accessed: 2024-10-30.

[14] Copernicus Open Access Hub. Copernicus open access hub, 2024. Accessed: 2024-11-09.

[15] Department of Water Affairs. Strategy and guideline development for national groundwater planning requirements: Potential artificial recharge areas in south africa. Technical Report PRSA 000/00/11609/1 - Activity 14 (AR04), Department of Water Affairs, South Africa, September 2009. Dated September 2009.

[16] Department of Water Affairs and Forestry (DWAF). Olifants River Water Management Area: Internal Strategic Perspective. Technical Report DWAF Report No P WMA 04/000/00/0304, Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa, 2004. Prepared by GMKS, Tlou and Matji, and WMB on behalf of the Directorate: National Water Resource Planning.

[17] Department of Water Affairs and Forestry (DWAF). Groundwater Resource Assessment II. Technical report, Department of Water Affairs and Forestry (DWAF), Pretoria, South Africa, 2006.

[18] Department of Water Affairs and Forestry (DWAF). Mpumalanga Groundwater Master Plan. Technical report, DWAF IS Project Office, Pretoria, South Africa, June 2008. Document Type: Groundwater Master Plan; Copy Printed Date: 2008-07-10.

[19] Department of Water Affairs (DWA). Development of a Reconciliation Strategy for the Olifants River Water Supply System: Groundwater Options Report. Technical Report WP 10197, Department of Water Affairs (DWA), Pretoria, South Africa, 2011.

[20] Department of Water Affairs, Republic of South Africa. Environmental management framework for the olifants and letaba rivers catchment areas (olemf), December 2009. Environmental Management Framework Report.

[21] Department of Water and Sanitation. Limpopo-olifants catchment management agency 2024-25 annual performance plan, 2024. Accessed: 2024-10-29.

[22] Chris Dickens, Gordon Craig O'Brien, Manuel Magombeyi, Patience Mukuyu, Brown Ndhlovu, and Nishadi Eriyagama. E-flows for the limpopo river basin: Basin report, report no. 2, 01 2020.

[23] Down to Earth. Agrovoltaics are a sustainable solution to india's solar energy land use challenges. *Down to Earth*, 2024.

[24] Down to Earth. Residential solar pvs face challenges in south africa: Low affordability compromises mass appeal. *Down to Earth*, 2024.

[25] Kaitano Dube. *Challenges and Opportunities Facing Higher Education in South Africa*, pages 11–27. Springer Nature Switzerland, Cham, 2024.

[26] Down To Earth. Solar mini-grid transforms lives of zimbabweans in rural areas, 2023.

[27] Engineering News. Sa innovation offers high-tech solution to energy crisis: Smart geyser devices integrated into household solar systems could significantly decrease residential load on eskom with potential to reduce household electricity bills by 80 *Crreamer Media's Engineering News*, 2023.

[28] European Space Agency (ESA). Copernicus digital elevation model (dem). Data retrieved from Copernicus Open Access Hub, 2021.

[29] Eskom. Eskom guidelines on use of system (guos), wheeling, offset, and banking of energy, 2021.

[30] Eskom. Transmission development plan (tdp) 2019-2029, 2021.

[31] Eskom. Wheeling concept introduction, 2022.

[32] Eskom Holdings SOC Ltd. Residential calculator. `https://www.eskom.co.za/distribution/residential-calculator/`, 2024.

[33] Alba Gómez-Arias, Lola Yesares, Joaquín Díaz, Manuel A. Caraballo, Maleke Maleke, Reinaldo Sáez, Esta van Heerden, Danie Vermeulen, José M. Nieto, and Julio Castillo. Mine waste from carbonatite deposits as potential rare earth resource: Insight into the phalaborwa (palabora) complex. *Journal of Geochemical Exploration*, 232:106884, 2022.

[34] J. Hendricks, B. Mhlanga, and J. Gumbo. Quantification of the impact of solar water heating and influence of its potential utilization through strategic campaign: Case study in dimbaza, south africa. *Energies*, 15(21):8283, 2022.

[35] L. Heng, D. P. F. de Vries, and M. M. G. D. De Groot. Soilgrids: Global soil information. Data retrieved from SoilGrids database, 2021.

[36] Deccan Herald. Rainwater harvesting must for large properties in bengaluru, assembly passes bill, 2021.

[37] ISRIC World Soil Information. Soil geographic databases, 2024. Accessed: 2024-11-09.

[38] Mehdi Jahangiri, Esther T. Akinlabi, and Sam M. Sichilalu. Assessment and modeling of household-scale solar water heater application in zambia: Technical, environmental, and energy analysis. *International Journal of Photoenergy*, 2021:1–11, 2021.

[39] Kruger to Canyons Biosphere. Projects, 2024. Accessed: 2024-11-05.

[40] M. Dinesh Kumar. Chapter 4 - comparing well irrigation with gravity irrigation. In M. Dinesh Kumar, editor, *Groundwater Economics and Policy in South Asia*, pages 81–104. Elsevier, 2023.

[41] Eskom Holdings SOC Ltd. *Transmission and Distribution of Electricity*. Eskom, 11 edition, August 2021.

[42] Dinesh M. Roof water harvesting for domestic water security: Who gains and who loses? *Water International - WATER INT*, 29:43–53, 03 2004.

[43] Roberts M. van Niekerk J. L. Meyer I., Reinecke J. Renewable energy short reports. Technical report, Stellenbosch University, 2024.

[44] Mining Review Africa. Palabora mining company saves r95 million in energy costs. *Mining Review Africa*, 2024.

[45] Mining Review Africa. Pioneering vent shaft at palabora holes out safely at 1,200 metres. *Mining Review Africa*, February 2024.

[46] Paul E. Misut and Clifford I. Voss. Freshwater–saltwater transition zone movement during aquifer storage and recovery cycles in brooklyn and queens, new york city, usa. *Journal of Hydrology*, 337(1):87–103, 2007.

[47] S.S.E. Mndaweni, S. Naicker, and D. Blake. Hydrostratigraphy of the malmani subgroup dolomites within the northeastern escarpment (limpopo and mpumalanga, south africa). *South African Journal of Geology*, 122(3):283–298, 2019.

[48] Municipalities.co.za. Ba-phalaborwa local municipality demographic information, 2024.

[49] Mopani District Municipality. 2022/23 draft annual report, 2023.

[50] Maxwell Musingafi. Fresh water sources pollution: A human related threat to fresh water security in south africa. *Journal of Public policy and Governance*, 1:72–81, 08 2014.

[51] Author's Name. Olifants river basin hydrology.

[52] Ndamulelo Nembilwi, Hector Chikoore, Edmore Kori, Rendani B. Munyai, and Tshilidzi C. Manyanya. The occurrence of drought in mopani district municipality, south africa: Impacts, vulnerability and adaptation. *Climate*, 9(4), 2021.

[53] German K. Nkhonjera and Megersa O. Dinka. Significance of direct and indirect impacts of climate change on groundwater resources in the olifants river basin: A review. *Global and Planetary Change*, 158:72–82, 2017.

[54] Department of Water and Sanitation. National state of water report 2022, 2022.

[55] Mary Funke Olabanji, Thando Ndarana, and Nerhene Davis. Impact of climate change on crop production and potential adaptive measures in the olifants catchment, south africa. *Climate*, 9(1), 2021.

[56] Mary Funke Olabanji, Thando Ndarana, Nerhene Davis, and Emma Archer. Climate change impact on water availability in the olifants catchment (south africa) with potential adaptation strategies. *Physics and Chemistry of the Earth, Parts A/B/C*, 120:102939, 2020.

[57] Sean Ong, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath. Land-use requirements for solar power plants in the united states. Technical Report NREL/TP-6A20-56290, National Renewable Energy Laboratory (NREL), 2013.

[58] OpenInfraMap. Openinframap, 2024.

[59] PowerOptimal. Case study: Elon - sustainable energy solution, 2024.

[60] Hassan Qudrat-Ullah. *Improving Rural Electrification Access in Cameroon: A Qualitative Study*, pages 7–36. Springer Nature Switzerland, Cham, 2024.

[61] ResearchGate. Nitrogen and water requirements for targeted yield of the main crops in turkey, 2024. Accessed: 2024-11-09.

[62] ResearchGate. Nitrogen required per area and per produced mass in the evaluated crops by brazilian farmers, 2024. Accessed: 2024-11-09.

[63] Hugo Retief and Sharon Pollard. Overview of water quality and quantity in olifants river catchment. Technical Report AID-674-A-13-00008, Association for Water and Rural Development (AWARD), Hoedspruit, Limpopo, South Africa, 2020. Compiled from reports by Hugo Retief, Neil Griffin, Caroline Palmer, Stephen Mallory, and Manuel Magombeyi.

[64] Hugo Retief and Sharon Pollard. Overview of water quality and quantity: Olifants river catchment, 2020. Funded by USAID: RESILIM-O project, Cooperative Agreement nr AID-674-A-13-00008.

[65] K. E. Saxton, W. J. Rawls, J. S. Romberger, and R. I. Papendick. Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal*, 50(4):1031–1036, 1986.

[66] I. Sekar and T. O. Randhir. Spatial assessment of conjunctive water harvesting potential in watershed systems. *Journal of Hydrology*, 343:39–52, 2007.

[67] SNV. Sustainable energy for rural communities: Mashaba solar mini-grid, 2024.

[68] South African Department of Water and Sanitation. Water Resources of South Africa, 2012 Study (WR2012), 2012. Accessed: 2024-10-31.

[69] South African Department of Water and Sanitation. Verified Hydrology Database, 2024. Accessed: 2024-11-08.

[70] South African Heritage Resources Agency (SAHRA). Appendix m - avifauna study, 2024.

[71] Statistics South Africa. Ba-phalaborwa local municipality.

[72] T. H. Thomas and D. B. Martinson. Roofwater harvesting: A handbook for practitioners. Technical Report Technical Paper Series No. 49, IRC International Water and Sanitation Center, Delft, The Netherlands, 2007.

[73] Louis Turc. Estimation of irrigation water requirements, a simplified method. *Agricultural Research*, 1(4):155–162, 1961.

[74] United Nations Development Programme (UNDP). Transforming lives: Solar mini-grid lights remote zimbabwe village, 2024.

[75] J.H.J. Van Vuren, H.H. Du Preez, and A.R. Deacon. Effects of pollutants on the physiology of fish in the olifants river (eastern transvaal). Technical Report 350/1/94, Water Research Commission, Pretoria, 1994.

[76] J.R. Vegter. Hydrogeology of Groundwater Region 19: Lowveld. Technical Report TT 208/03, Water Research Commission, Pretoria, South Africa, October 2003. WRC Consultancy No. K8/463.

[77] Wazimap. Ba-phalaborwa municipality profile, 2024.

[78] World Economic Forum. Agrivoltaic farming: how to harness the sun for food and energy. *World Economic Forum*, 2022.

[79] WSM Leshika Consulting (Pty) Ltd. Groundwater Specialist Report for Phalaborwa Filling Station Extension, Limpopo Province. Technical report, WSM Leshika Consulting (Pty) Ltd., Limpopo Province, South Africa, July 2020. Project Number: WH20019, Report Version: V1.0.

Appendix A

Water

A.1 Available Water Capacity

The soil water retention properties, specifically Permanent Wilting Point (PWP), Field Capacity (FC), and Available Water Content (AWC), were calculated based on clay and sand content at 30-60 cm extracted from SoilGrids [35]. This depth was assumed optimal for assessing soil moisture availability for plant roots. The clay and sand content was initially provided in grams per kilogram (g/kg) and converted into percentage values. Subsequently, the PWP, FC and AWC were calculated in accordance with the Saxton method [65] as follows:

$$a = \exp(-4.396 - 0.0715 \cdot clay_{\%} - 0.000488 \cdot sand_{\%}^2 - 0.00004285 \cdot sand_{\%}^2 \cdot clay_{\%}) \tag{A.1}$$

$$b = -3.14 - 0.00222 \cdot clay_{\%}^2 - 0.00003484 \cdot sand_{\%}^2 \cdot clay_{\%} \tag{A.2}$$

$$\text{PWP} = (\frac{15}{a})^{\frac{1}{b}} \tag{A.3}$$

$$\text{FC} = (\frac{0.33333}{a})^{\frac{1}{b}} \tag{A.4}$$

$$\text{AWC} = \text{FC} - \text{PWP} \tag{A.5}$$

The AWC values obtained from these calculations ranged from 0.08 to 0.25 cm/cm, which is reasonable for semi-arid regions, where available moisture content tends to be limited but sufficient for certain drought-resistant plants.

A.2 Water Maps

Here one can find the maps that were used throughout the analysis for the water balance, some were sourced from WR2012 [68]. It should be noted that in order to get full access, an account must be created and the custodian must be contacted.

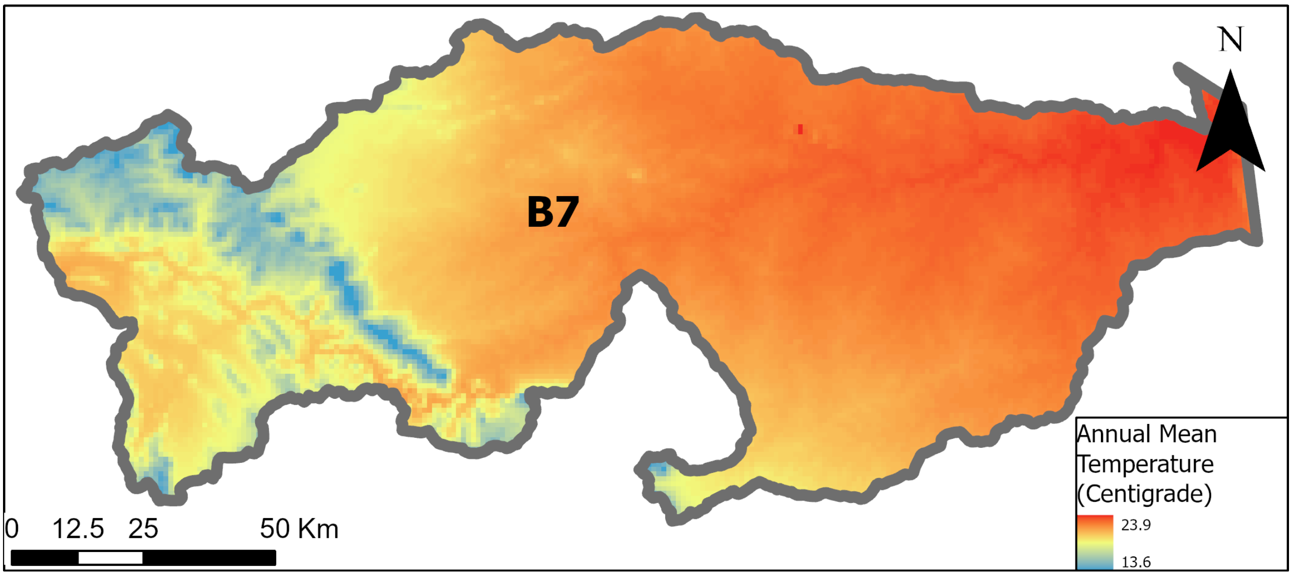


Figure A.1: Annual Temperature map from WR2012, in combination with this map and the data from Visual-Crossing the monthly maps and values were computed

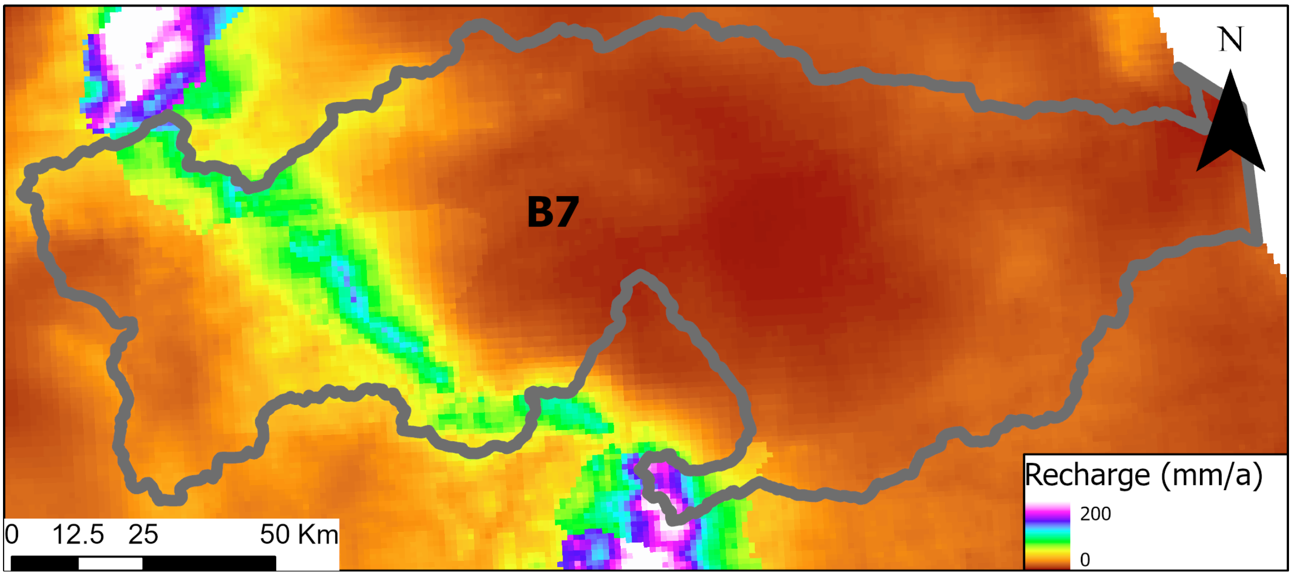


Figure A.2: Annual Recharge map from WR2012

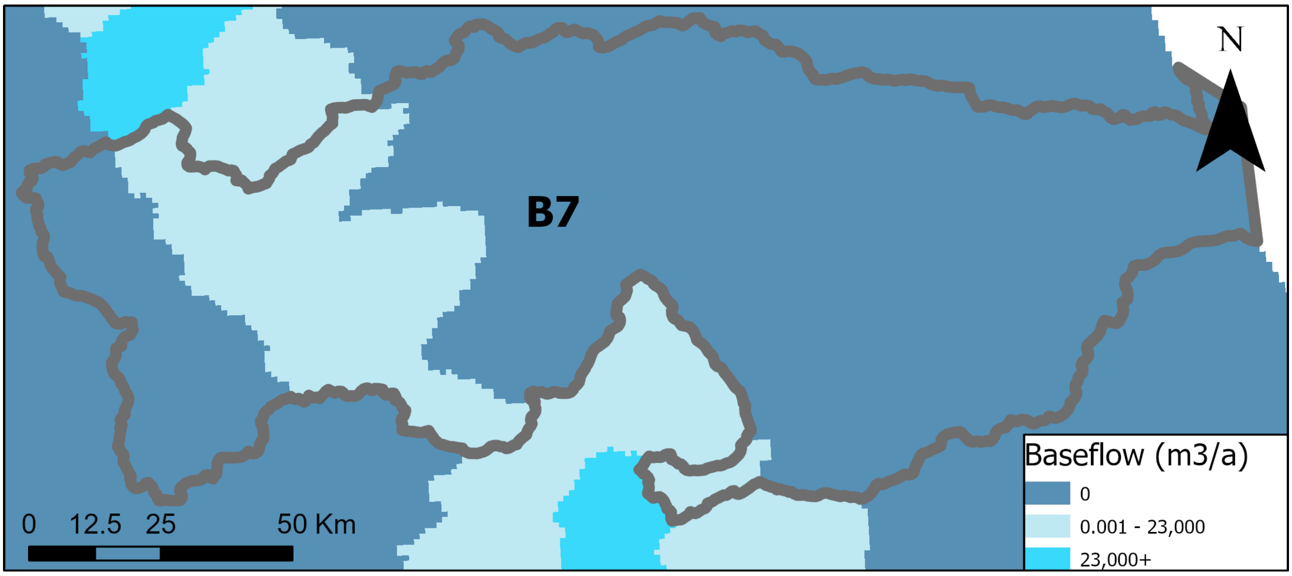


Figure A.3: Annual Baseflow map from WR2012

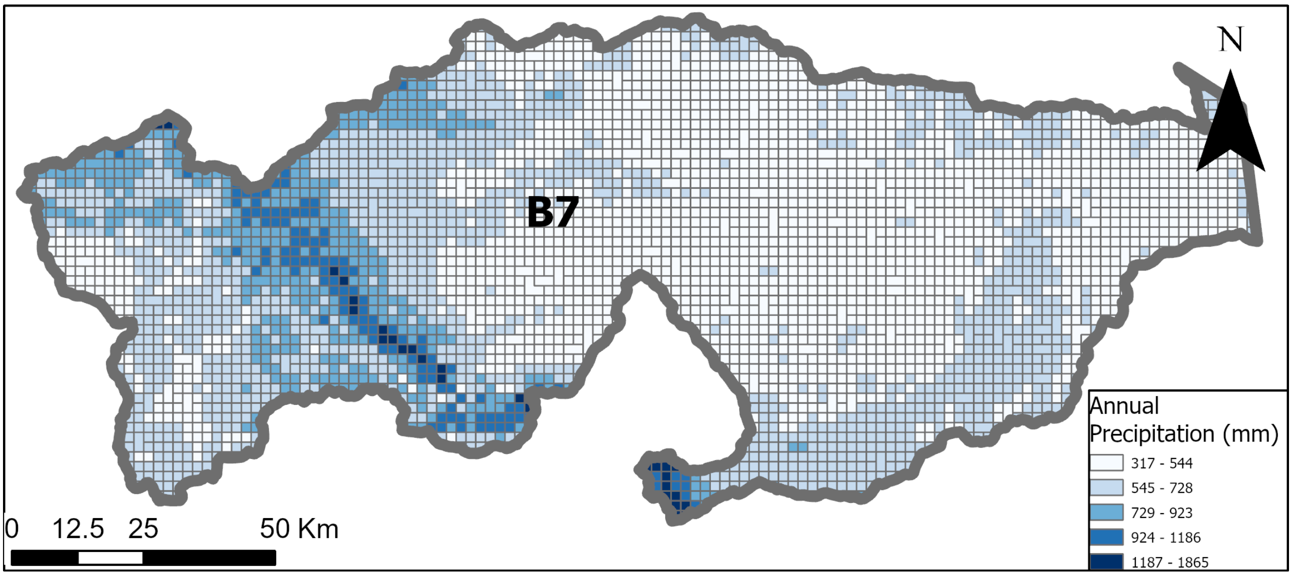


Figure A.4: Annual Precipitation map from WR2012, in combination with this map and the data from Visual-Crossing the monthly maps and values were computed

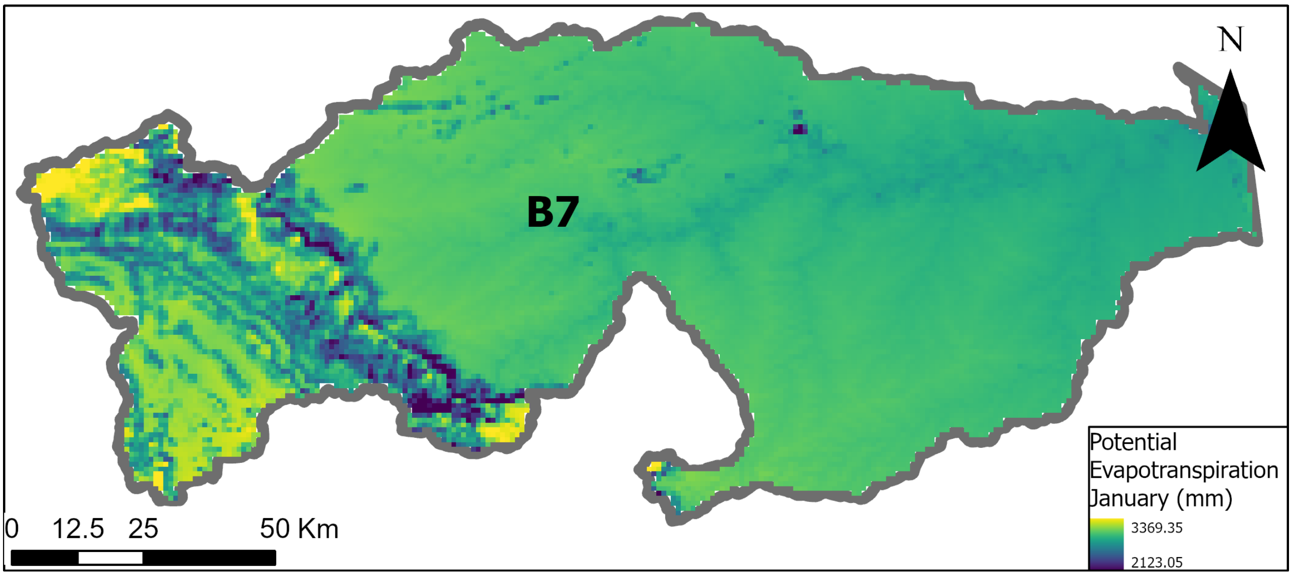


Figure A.5: Potential Evapotranspiration map of January, as calculated by the Turc method (mm/a)

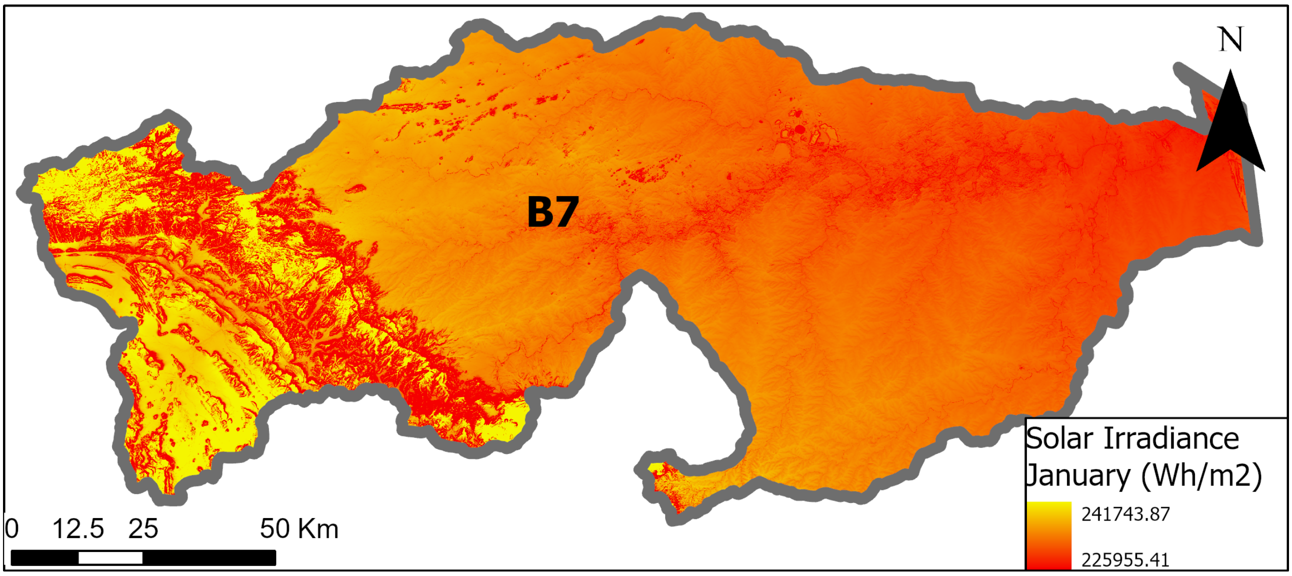


Figure A.6: Solar Irradiance map of January computed with the ArcGIS Pro Solar Area tool, maps for every month were computed

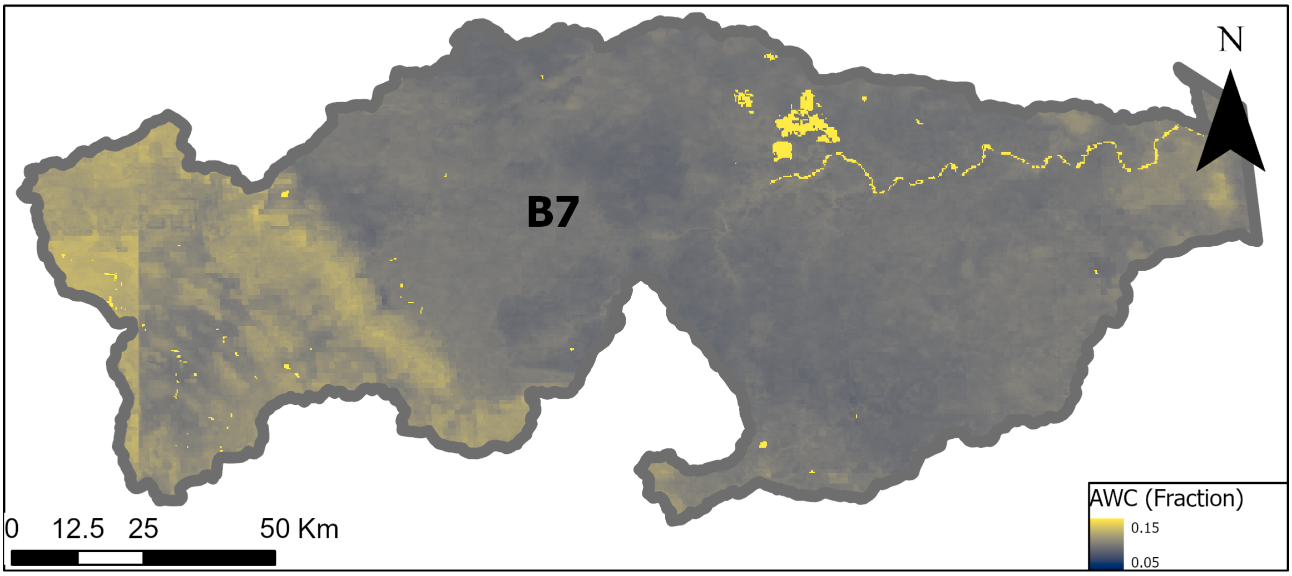


Figure A.7: Available Water Capacity Map

Appendix B

Food

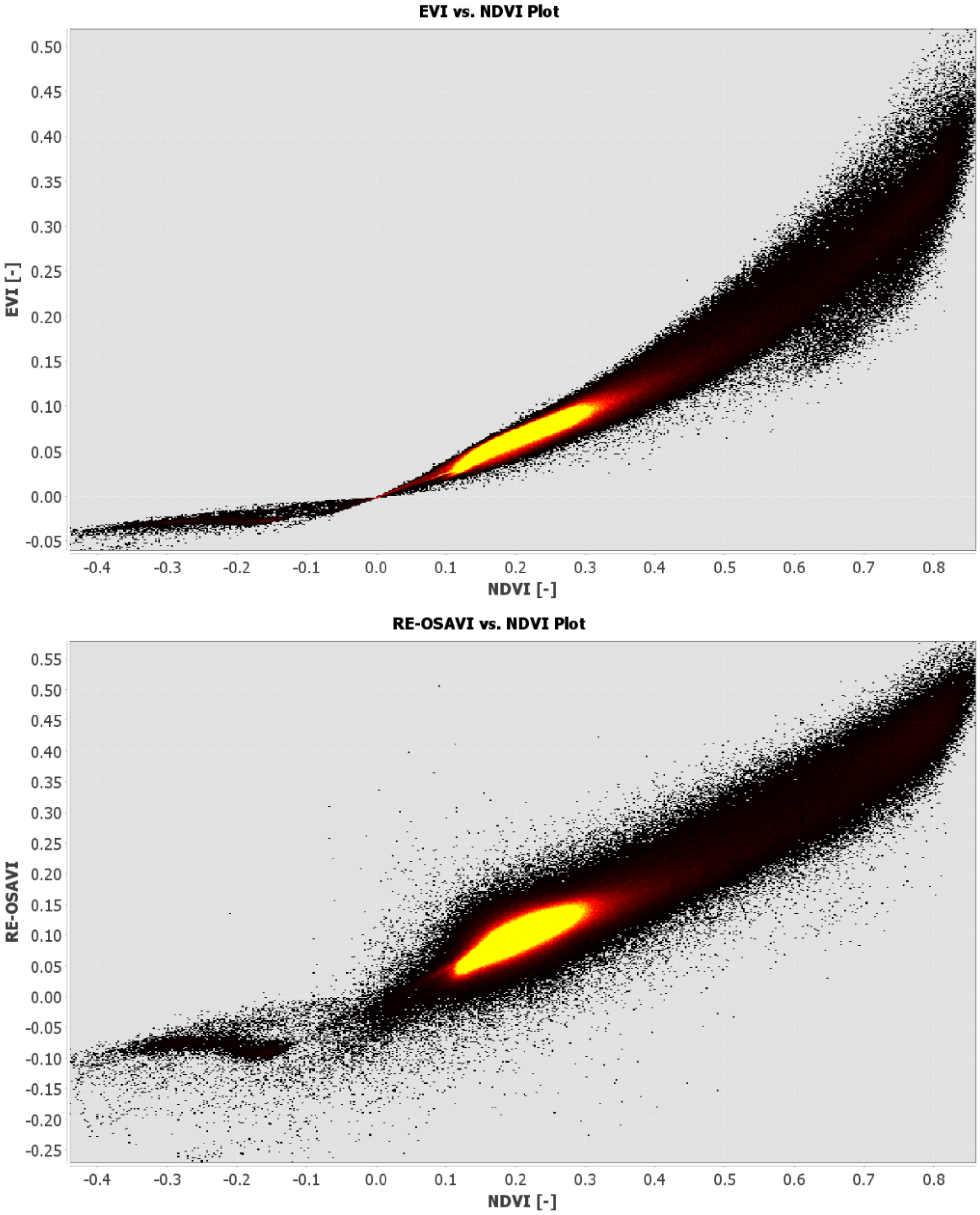


Figure B.1: NDVI

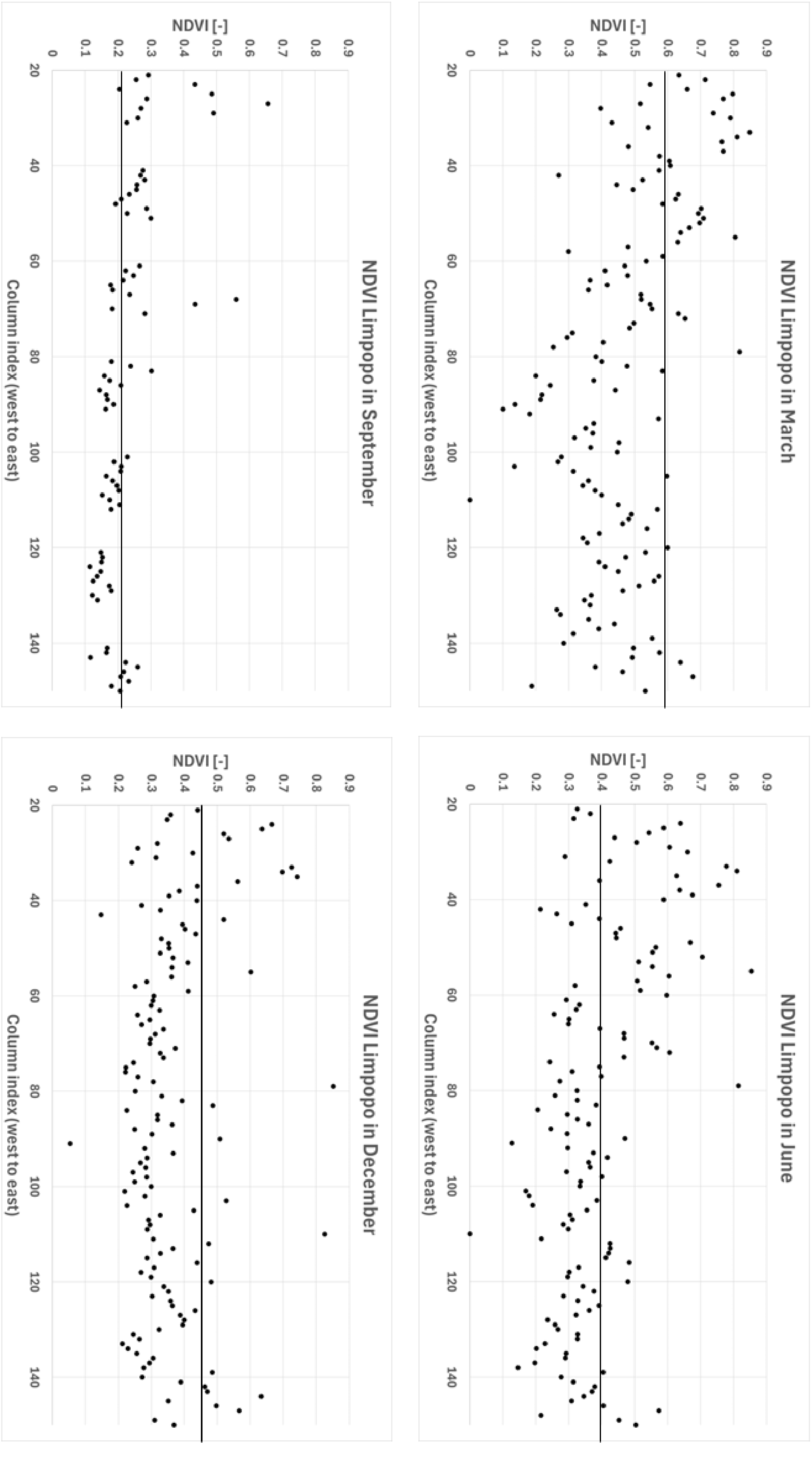


Figure B.2: Your figure caption

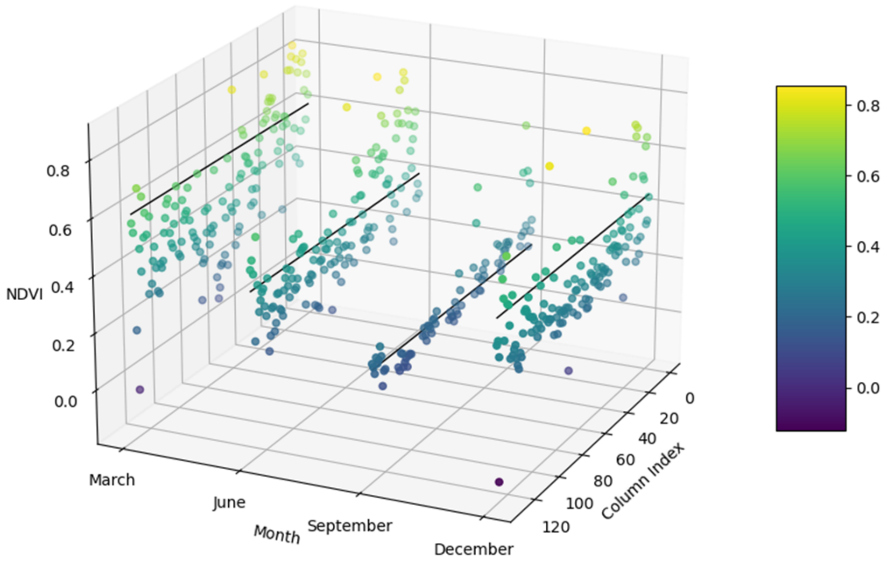


Figure B.3: NDVI 3D graph

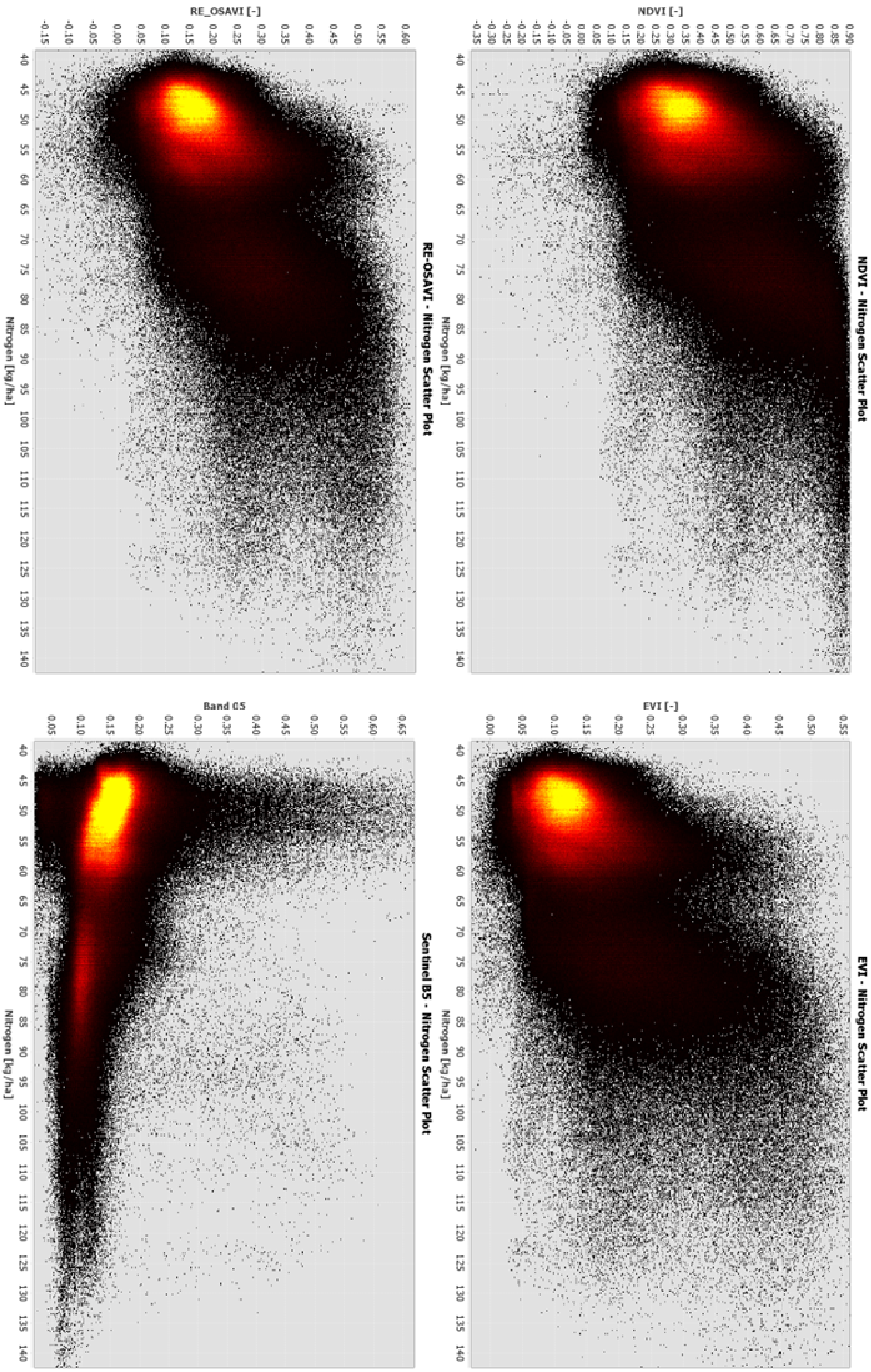


Figure B.4: Your figure caption