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Engineering a River-based Irrigation Scheme: Case study of the Bonosha Farm in Southern Ethiopia

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Abstract

Effectively engineering irrigation systems remains a challenging endeavor for many agricultural projects in the Global South. While public data for an approximate analysis of appropriate irrigation systems is often available, it frequently remains underutilized. The following thesis conducts a case study, estimates the irrigation water demand, and proposes an irrigation layout for the Bonosha farm in SNNPR, Ethiopia. Utilizing the open-access software products FAOstat, QGIS, ClimWat, CropWat, and EPAnet, the thesis exclusively relied on utilizing public data to achieve its set objectives. The thesis itself presents a framework for an approximate analysis and the engineering of a river-based irrigation scheme in data and financially scarce project environments.

Keywords: Ethiopian Agriculture, QGIS, Cropwat, Net Irrigation Water Demand, EPAnet, Irrigation Framework

Introduction

Engineering a water and energy efficient irrigation scheme to improve the overall viability of an agricultural operation has been a defining feature for strategically increasing economic prosperity in Ethiopia, where agriculture is estimated to be accountable for 47.7 percent of the total GDP [1]. The development of a viable and efficient irrigation scheme is often claimed to be one of the major challenges when planning an agricultural venture [2]. It is commonly known that irrigating crops positively influences growth yields [3]. However, while an efficient irrigation scheme is key for the success of an agricultural venture, it is currently rarely established in most Ethiopian agricultural projects. For instance, research from the FAO claims that the overall irrigation development in Ethiopian agricultural is around 5 to 6 percent, from which the majority of farms are assumed to be exclusively irrigated via river water [4].

Previous multidisciplinary studies explored different established irrigation schemes in Ethiopia, the suitability of irrigation schemes, or the impacts of different land covers on land usages [5, 6, 7]. In particular, agricultural research has demonstrated the importance of irrigation techniques through several case studies and experiments involving a wide range of crops, soil types, climates, and irrigation water quality and quantity [8, 9, 10]. Different publications, such as Hameed et al. 2023 or A. Rasheed and Al-Adili 2016, have used open-access software for both estimating the irrigation water demand and for technically planning an irrigation scheme [11, 12]. Despite the knowledge and research about irrigation techniques, there is no blueprint for the individual choice of an irrigation scheme [13]. While several criteria, such as available water sources, soil characteristics, and local climate, are fundamental for the planning, the specific context of the venture and further background information should be accounted as well. Therefore, the technical planning of an irrigation scheme remains an adapted procedure to address the project´s individual circumstances [14].

This raises the questions of what parameters ought to be mandatory for the planning of an irrigation scheme and how the individual context can be considered, especially when data and financial capacities are scarce.

Outline

Following this introduction, relevant literature is reviewed, and materials and methodology are presented. Subsequently, the thesis demonstrates a reproducible method to engineer irrigation schemes in data-scarce projects, by developing an irrigation scheme for the case study. Firstly, serving as the fundamental basis for this work, information about the case study and the study site is collected, organized, and presented. Thereafter, the crop pattern and crop scheme are laid out, followed by an estimation of the crop water demand and the planning of the crop irrigation schedule. The main section then shows the selected irrigation scheme layout and its characteristics. Finally, the study addresses relevant data gaps as well as future objectives to further evaluate the findings and optimize the irrigation scheme at the case study - Bonosha farm.

Research Design

The research of this thesis is exclusively performed by using public data and open-access software. The thesis follows an approximative approach. Furthermore, a case study is being utilized to make the presented concepts and processes more tangible.

Case Study

The thesis engineers an irrigation scheme for the Bonosha farm, an agricultural venture in SNNPR Ethiopia. The irrigation water will be drawn from the nearby river, called Bilate. As the venture of the Bonosha farm is currently in the state of initial planning, no irrigation scheme has yet been installed. Therefore, the choice and subsequent development of an adequate irrigation scheme influences the further planning processes and with it the overall success of the venture.

As stated by the owner of the land, Bereket Forsido Menedo, and a project consultant Dr. Ulrich Kögler, it is planned to grow highly valuable vegetables, such as spinach, broccoli, parsley, and beans. After planting, growing, and harvesting, the crops should be washed and thereupon exported to the GCC countries, while a lower percentage is planned to be exported to northern EU markets. The objective is to secure daily fresh vegetable exports. Therefore, the implementation of a cultivation program including harvesting and planting crops of three to four times per year is aspired.

The given objectives and requirements for the irrigation scheme are to be:

1 Reliable throughout the year

2 Suitable for river water with high sediment containment

3 Water and energy efficient

4 Cost efficient in Capital Expenditure (CapEx) as well as Operational Expenditure (OpEx)

Besides the irrigation system, the venture includes planning of processing and cooling units, energy and transportation infrastructure, waste management as well as different aspects of general business development.

Further economic observations have to take into consideration that firstly, all needed machinery, and most of the required materials, must be purchased from overseas at global market prices and secondly, that the produced vegetables have to be air-cargoed to the corresponding consumer markets at around 1,2 $/kg [15].

The venture aspires to employ civilians, cooperate with local initiatives and organizations, and provide sensible services, such as drinking water and sanitation to the nearby communities. This aims to locally increase the project acceptance, while improving livelihood and spreading prosperity among the region.

Relevance

The thesis contributes to creating an in-depth decision-making process regarding the choice of a viable and efficient irrigation scheme in data-scarce project environments. While irrigation is crucial for modern-day farming and can be accounted as standard in Western agriculture, the prevalence of irrigated agriculture in Ethiopia is marginal [16].

FAO and many more calls for an increasing development in irrigation in Ethiopian agriculture [17]. These rising interests and efforts to increase the usage of irrigation techniques in Ethiopia are driven by various parties. The Ethiopian government stated to support farmers by funding irrigation systems [18]. Additionally, the Agricultural Growth Program (AGP) was implemented to further support the agricultural development in Ethiopia. AGP is supported by Ethiopia, as well as other countries, like Australia and Germany, or NGOs like the Bill and Melinda Gates Foundation. In total, AGP invested $51.5 million in Ethiopia during the first funding stage [19]. In this context, the process of engineering an irrigation scheme with public data and open-access software not only empowers farmers to plan an irrigation scheme by themselves, but can also enhance third-party endeavors towards remotely evaluating the viability of irrigation schemes. By means of the case study, the practicability of remotely engineering an irrigation scheme is showcased, while being transparent about uncertainties, volatilities, and further limitations of the thesis.

Limitations

The scope of this thesis does not cover the inclusion of all influencing factors for the engineering of an irrigation scheme. For instance, the river-water quantity and quality, the nutrient composition of the soil, or more detailed data about the crop growing stages are not being covered, even though they would further specify and enrich the thesis findings. Significant data about the mentioned parameters is currently unavailable. Thus, the study attempts to cope with this lack of information.

Wherever possible, public data was used. However, it should be noted that some datasets may be outdated by now, are partially limited in resolution, and cannot always be independently evaluated, which presents a challenge regarding their utility.

The biggest limitations to the thesis are the restrictions of performing experiments and empirical analysis, taking samples, and communicating with local experts and organizations on site. These limitations are partially rooted in the wider political circumstances and safety concerns within Ethiopia. They were consciously accepted by the author, to create a thesis framework that can be applied on numerous occasions and ventures facing similar limitations.

Keeping these limitations in mind, the outcomes of this thesis should be viewed as approximations towards reality that need further inspection and confirmation through data acquisition and empirical analysis. If the circumstances allow, these should preferably be performed on-site.

Literature Review

This literature review serves as an introduction to the concepts and contents applied in the engineering of an irrigation system for the case study. The review builds a basis for understanding the factors being used to describe the study site.

The literature review is structured into three parts to enhance clarity. It commences by introducing remote sensing and Web-GIS as a method and a tool to build a knowledge foundation for the thesis. Subsequently, a review of different agricultural parameters and their role in the estimation of the net irrigation water demand is presented. Thereafter, different irrigation technologies are introduced and compared, to enable the further selection of a viable irrigation technology.

Additionally, it should be mentioned that the thesis makes use of a broad variety of research, data, and publications, especially those performed or financed by the FAO, as well as those performed or published within the scope of Ethiopian research.

Remote Sensing and Web-GIS in Agriculture

Remote sensing, as the term suggests, involves acquiring information and data from distance. Early-stage remote sensing technologies usually implied observing the field from an elevated point of view, however, since then, remote sensing technology has developed rapidly. Previously making observations via hot air balloons, helicopters, and rockets, the current state-of-the-art technology remotely senses areas by utilizing satellite images and space stations [20].

Remote sensing technologies have increased the efficiency of agriculture by various applications. Besides its usages for crop monitoring and pest management, remote sensing technologies are being used for irrigation management and yield prediction. Technological developments in information and communication, such as remote sensing or GIS systems, are so disruptive innovations, that they are stated to be the primary drivers of the so-called fourth agricultural revolution [21].

Satellite imagery and remote sensing in agriculture can for example provide information regarding land use and land coverage, soil types and characteristics, or the terrains topography [7, 6]. Remote sensing further enables the development of Web-GIS databases, like the Web application FAOSTAT from the FAO hand-in-hand initiative. Such tools enable open access to thematically clustered information and geo-data [22].

Khanal et al. 2020 offer a comprehensive investigation of the accomplishments, opportunities, and limitations of remote sensing in agriculture [23]. While remote sensing is applicable for broad usages, it still needs to be further developed and investigated in some fields, such as soil compaction and grain quality monitoring, to outperform conventional analysis and monitoring methods. Furthermore, data accuracy highly depends on the input data quality, like the scale and the resolution of the utilized satellite images [23].

As the case study is partially characterized by data scarcity, remote sensing and satellite imagery provide necessary insights for the analysis of the study site.

Agricultural Parameters

Agricultural parameters can be organized into four categories. Figure 1, generated by Torres-Sanchez et al. 2020, visualizes the potential data sources for agriculturally used parameters and gives examples of key parameters within each one.

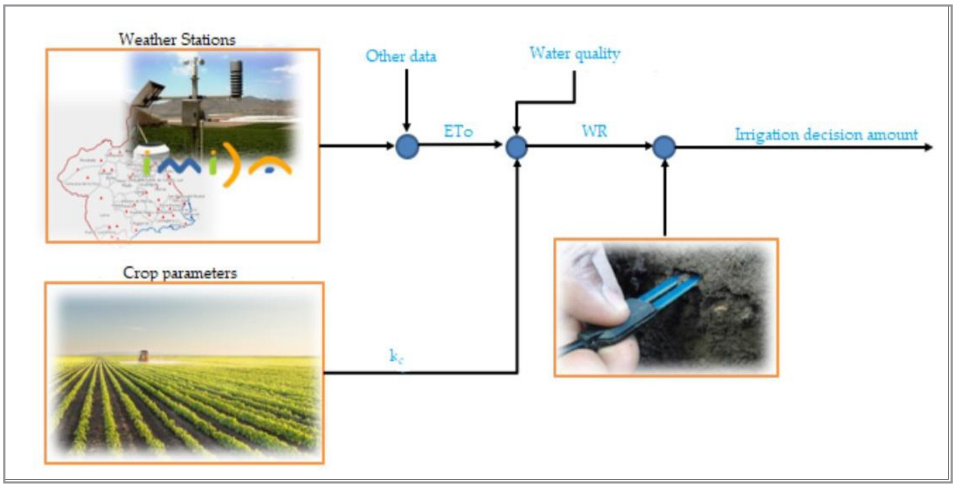

Figure 1: Data sourcing processes to determine irrigation demand [24]

Firstly, climatic parameters, such as temperature, wind speed, precipitation, humidity, radiation, and more are collected by weather stations. Fluctuations in this data, during the seasons, and even throughout long-term observation periods are categorized as climatic fluctuations and not as weather conditions or events [25]. In addition to the naturally occurring fluctuations, anthropogenic climate change is drastically causing harmful climatic conditions for organisms and ecosystems. Harsh climatic conditions and the difficulty of precisely predicting future regional development of climatic parameters are challenging many industries, including agriculture and irrigation planning [26].

Secondly, crop parameters, such as the kc-value or the crop height, are setting the boundaries and partially shaping the requirements of the applied irrigation system. Different crop types and sub-types show various behaviors and requirements on water quantity, quality, climate parameters, and more [3].

Thirdly, the water quality and quantity are influencing the suitability and selection of a proper irrigation system. Water can contain certain amounts of nutrients, as well as potentially toxic containments or larger sized particles. Information about water sources applicable for irrigation is crucial for safely managing and optimizing irrigation in agriculture [27].

Fourthly, the soil characteristics, such as the water retention capacity of the soil or the salt excess, influence water management, plant growth, and with it the overall irrigation planning [28].

Climate

Reference evapotranspiration (*ET*0) – The reference evapotranspiration (*ET*0), representing the evapotranspiration rate from a reference crop, that is not limited by water availability, is a pivotal parameter in agricultural hydrology. The inception of the concept of *ET*0 was driven by the necessity to comprehend the atmospheric evaporative demand, independently of crop-specific variables and agricultural practices. The reference evapotranspiring surface, characterized by abundant water availability, ensures that the soil-specific factors do not influence *ET*0. This standardization allows for the establishment of a reference point to which evapotranspiration from diverse surfaces can be correlated. The usage of *ET*0 eliminates the need to define distinct evapotranspiration levels for various crops and growth stages.

Crucially, *ET*0 is exclusively governed by climatic parameters, rendering it a climatic variable that can be computed using climate data. This permits the comparison of *ET*0 values across different locations and seasons, as they all are based on evapotranspiration from the same reference surface (Allen et al., 1998).

Penman-Monteith method - The most common method to determine the *ET*0 is the Penman- Monteith method, developed by FAO (Equation 1). It is widely applied due to its consistent results for *ET*0 in global crop use patterns.

Equation 1: Reference Evapotranspiration

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$

where:

- ET_0: reference evapotranspiration [mm day-1]
- Rn: net radiation at the crop surface [MJ m² day-1]
- G: soil heat flux density [MJ m² day-1]
- T: mean daily air temperature at 2 m height [°C]
- U_2: Wind speed at 2 m height [m s-1]
- e_s: saturation vapour pressure [kPa]
- e_a: actual vapour pressure [kPa]
- Δ slope vapour pressure curve [kPa °C-1]
- Γ: psychometric constant [kPa °C-1]

The Penman-Monteith method is characterized by the implementation of physiological and aerodynamic parameters, rectifying the limitations of earlier state-of-the-art methodologies. Moreover, it accommodates situations of limited climatic data availability, further enhancing its applicability in various agricultural contexts. Therefore, the Penman-Monteith method is a robust tool for assessing □□0, contributing to a detailed understanding of atmospheric evaporative dynamics in agricultural settings [29].

Rain

Total rainfall – The sum of precipitation, in mm, over a set period is defined as the total rainfall (Equation 2). The total rainfall is often being utilized for the quantification of a raining event.

Equation 2: Total Rainfall 1

$$total\ rainfall = \sum_{i=1}^{n} P_i$$

The parameter can be utilized for water balance calculations. The total rainfall can be separated into the effective rainfall and the rainfall losses (Equation 3).

Equation 3: Total Rainfall 2

$$total\ rainfall = effective\ rainfall + rainfall\ losses$$

Rainfall losses – The fraction of rainfall that cannot be used by crops is defined as rainfall loss. Rainfall losses are due to surface runoff, as well as deep percolation and can therefore be calculated as the sum of both (Equation 4).

Equation 4: Rainfall Losses

$$rainfall\ losses = surface\ runoff + deep\ percolation$$

Effective Rainfall – The portion of precipitation utilizable by crops is defined as effective rainfall. The effectiveness of rainfall depends upon multiple factors, including soil type, slope, crop canopy, storm intensity, and initial soil water content. As the interaction of the influencing factors is complex, accurate assessment of effective rainfall necessitates field observations. Minimal or absent runoff signifies highly effective rainfall as a larger proportion of rain permeates the soil. Conversely, small rainfall amounts may not effectively contribute to soil moisture as they are susceptible to quick losses through evaporation [30, 31].

Dependable Effective Rainfall (FAO/AGLW formula) - In the realm of effective rainfall estimation, various approaches are employed, each tailored to capture the complex dynamics of precipitation and its utilization by crops. The FAO/AGLW formula was developed for arid and sub-humid climates. It introduces a comparably intricate calculation for dependable effective rainfall, considering the combined effects of dependable rainfall (80% probability of exceedance) and estimated rainfall losses. The equations 5 and 6 vary based on monthly and decadal steps, reflecting the climatic nuances [32].

Equation 5: Dependable Effective Rainfall (monthly)

$$P_{eff} = 0.6 * P - 10 \qquad \text{for } P_{month} \le 70 \text{ mm}$$

$$P_{eff} = 0.8 * P - 24 \qquad \text{for } P_{month} > 70 \text{ mm}$$

where:

P_{eff}' effective rainfall in [mm]

P rainfall in [mm]

Equation 6: Dependable Effective Rainfall (decadal)

$$P_{eff(dec)} = 0.6 * P_{dec} - 10 \quad \text{for } P_{dec} <= (70/3) \text{ mm}$$

$$P_{eff(dec)} = 0.8 * P_{dec} - 24/3 \quad \text{for } P_{dec} > (70/3) \text{ mm}$$

where:

$P'_{eff\ (dec)}$ effective rainfall per 10 days in [mm]

P_{dec} rainfall per 10 days in [mm]

Soil

The soil type and its characteristics play a vital role in irrigation planning and agriculture. The soil provides the plants with nutrients and acts as a water storage. To simplify the categorization of soils, figure 2 displays the USDA soil triangle (USDA, n.d.) [33]. The soil triangle presents commonly applied methods to characterize soil by measuring its clay, silt, and sand proportions (Scherer, 2022). The USDA soil triangle calculator can be found in the appendix 1.

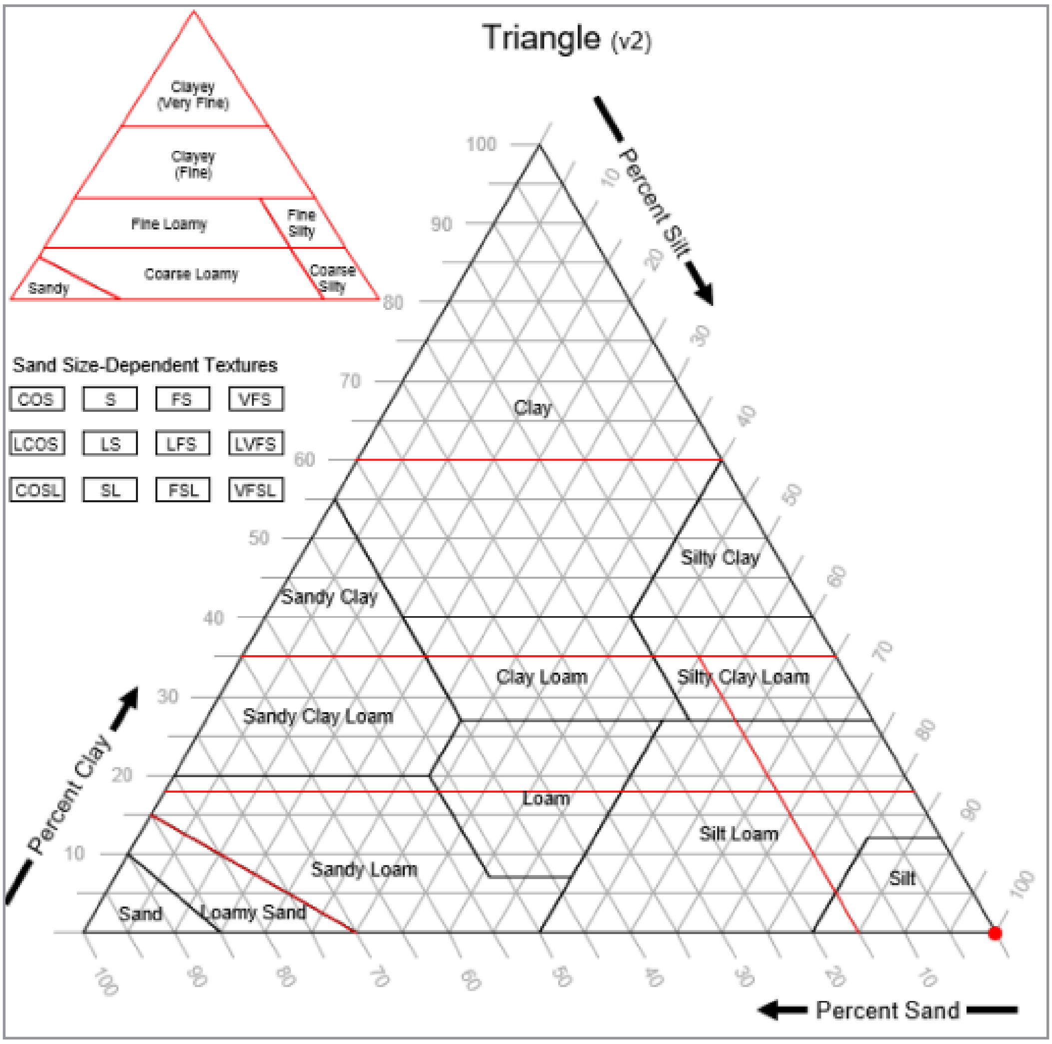

Figure 2: USDA soil triangle used to characterize soils (USDA, n.d.)

Further soil parameters, such as field capacity or soil water retention, can be estimated by applying the Van Genuchten model [34]. A visualization of common soil characteristics used in agriculture is given in figure 3.

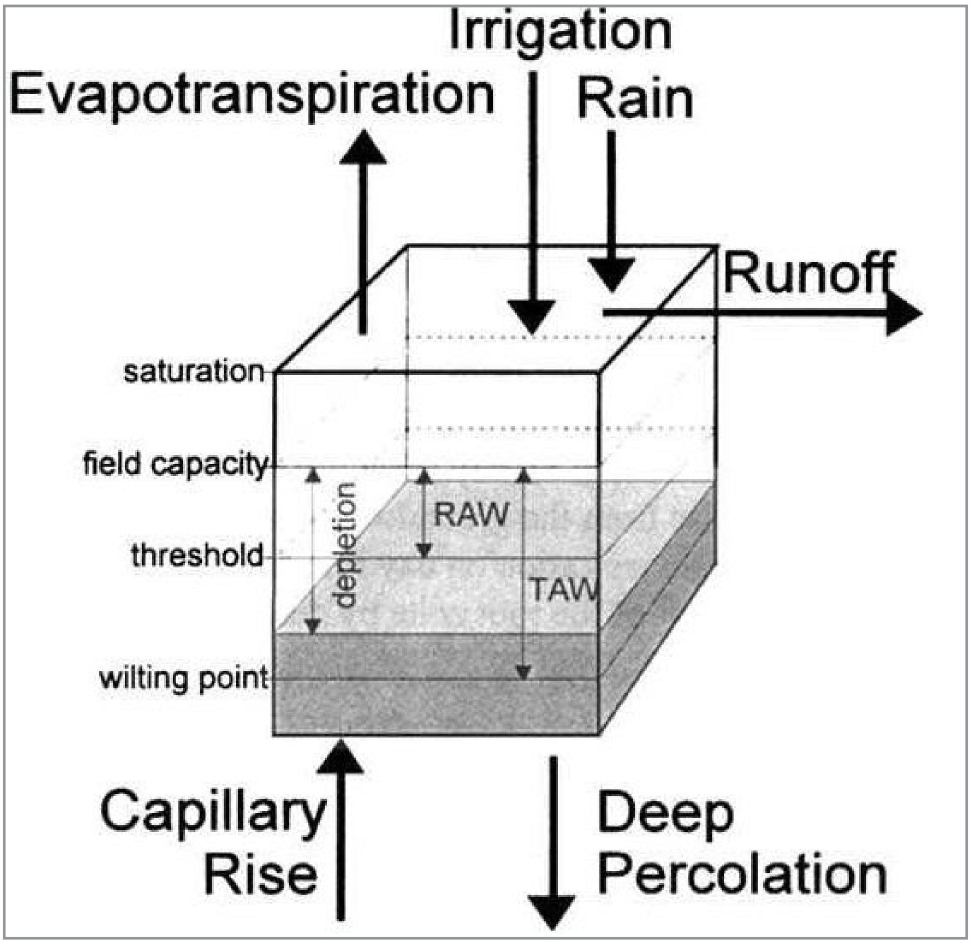

Figure 3: Visualization of Water Balance Elements in the Root Zone [35]

Total Available Water (TAW) - The total water accessible to crops is defined as the sum of Field Capacity (FC) and Wilting Point (WP) (Equation 7).

Equation 7: Total Available Water

$$total\ available\ water = field\ capacity + wilting\ point$$

TAW indicates the moisture content that can be utilized by plants for growth and development. The determination of TAW relies on the soil´s textural, structural, and organic matter characteristics [36].

Initial Soil Moisture Depletion - The quantitative measure indicating the dryness of the soil at the start of the growing season is defined as the initial soil moisture depletion. It is calculated at seeding as the percentage of TAW, denoting the extent of depletion from Field Capacity (FC) (Equation 8).

Equation 8: Initial Soil Moisture Depletion

$$inital\ soil\ moisture\ depletion = \frac{(FC - soil\ moisture\ at\ seeding)}{TAW} * 100$$

A default value of 0% signifies a fully wetted soil profile at FC, while 100% represents a soil condition at Wilting Point (WP). The estimation of the Initial Soil Moisture Depletion relies on previous crop data and the periods of preceding rain or dry seasons [36].

Initial Available Soil Moisture – In agricultural management, the initial available soil moisture is defined as the soil moisture content that is available to crops at the beginning of their growing cycle. Its computation goes by the multiplication of Total Available Water (TAW) by the Initial Soil Moisture Depletion, expressed in millimeters per meter of soil depth (Equation 9) [53].

Equation 9: Initial Available Soil Moisture

$$initial\ available\ soil\ moisture = TAW * initial\ soil\ moisture\ depletion$$

Maximum Infiltration Rate – The maximum infiltration rate, expressed in millimeters per day, represents the amount of water that can infiltrate the soil over 24 hours. It depends on the soil type, the slope class, and the intensity of rainfall or irrigation. This parameter, equivalent to the soil hydraulic conductivity under saturation, enables the estimation of runoff when precipitation intensity surpasses the soil's infiltration capacity [16].

Maximum Rooting Depth - The concept of Maximum Rooting Depth expresses the deepest point, in centimeters, within the soil where plant roots can effectively extract water. While often genetically determined by the crop, the presence of certain soil layers, such as hardpans, can impose restrictions on rooting depth. Any value below the genetically determined crop's rooting depth implies restrictions to root development [16].

Crops

Crop Stages – The conceptional segmentation of the crop growing cycle into four stages allows a practical distinction of crop parameters and analysis (Figure 4). Applications of the crop stages concept are to the stage-allocated yield response, or the evapotranspiration influenced by the ground coverage of the crop [17].

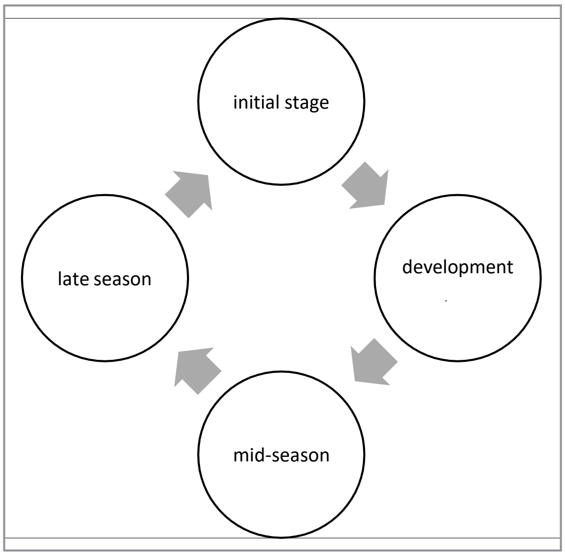

Figure 4: Stages of the crop growing cycle [37].

Starting with the initial stage, whose duration highly depends on the crop, planting date, and climate, the ground coverage is approximately 10%. Secondly, the development stage can be characterized by the increase of leaf growth leading up to full effective ground coverage. The mid-season stage comes third. In this stage, the crops transition from full coverage to the start of maturity, even up to showing the first signs of aging, like yellow leaves or browning of the fruit. Usually, the mid-season has the longest duration, as well as the highest yield response, among the different stages. Fourthly, the late season, in which the crop runs from the start of maturity to harvest, closes the crop growing cycle. Besides the crop type, the climatic growth conditions, especially the temperature, influence the length of each stage [37].

Crop Coefficient (*Kc*) – To distinguish the specific crop planted from the reference crop, the empirically estimated crop coefficient *Kc* can be applied. The main influence on the crop coefficient is the crop type. Additionally, the *Kc*-value varies during the different growing stages and the frequency of wetting events. The development of the *Kc*-value during the different growing stages is presented in figure 5.

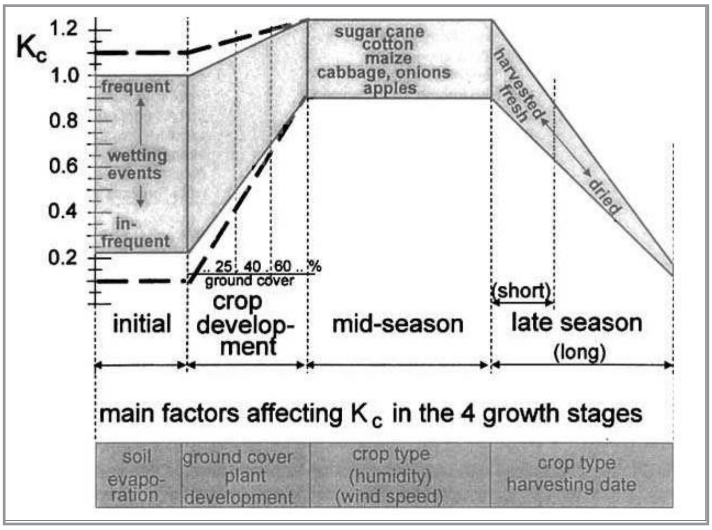

Figure 5: Factors Kc-value during the growing stages [26].

Crop Evapotranspiration under standard conditions (*ETc*) – In accordance with the crop coefficient approach, the *ETc* describes the evapotranspiration a of a disease free, well- fertilized crop that grows in large field under optimum soil water conditions. *ETc* is calculated by multiplying the Crop coefficient *Kc* by the reference evapotranspiration ET_0 (Equation 10) [29].

Equation 10: Crop Evapotranspiration Under Standard Conditions

$$ET_c = K_c * ET_0$$

Yield reduction - The reduction of yield, due to soil moisture stress, in comparison to the maximum production yield under optimal conditions, can be expressed in % by referencing a single stage, or the whole growing season of a crop cycle [3]. The yield reduction is calculated by applying the following equation 11:

Equation 11: Yield Reduction

$$yield\ reduction = \left(1 - \frac{Y_a}{Y_{max}}\right) = K_y * (1 - \frac{ET_{c(adj)}}{ET_c})$$

where:

- *Ya*: Yield achievable under actual conditions
- *Ymax*: Maximum crop yield achievable in case of full satisfaction of crop water needs
- K*y*: Yield response factor
- *ETc*(*adj*): Crop evaporation under non-standard conditions
- *ETc*: Crop evaporation under standard conditions

Irrigation Systems

Irrigation systems are designed to ensure optimal crop growth by supplementing natural rainfall with irrigation [3]. The individual needs influence the viability and choice of an irrigation system. There are countless different irrigation techniques and systems all over the world [36]. This thesis will focus on systems for mixed irrigation, that are commonly used in today's agriculture.

Irrigation Parameters

Irrigation requirement – The irrigation requirement is calculated as the difference between the effective rainfall and the crop evapotranspiration under standard conditions (Equation 12).

Equation 12: Irrigation Requirement

$$irrigation\ requirement = ET_c - Peff$$

As the name indicates, the irrigation requirement represents the water that needs to be irrigated to achieve optimal crop-growing conditions [3].

Irrigation efficiency - Irrigation efficiency describes how efficiently the irrigation water is applied and used in an agriculture venture. For a well-managed gravity irrigation, the default value of 70% is recommended. Water losses and decreasing irrigation efficiency can occur, mainly depending on the land leveling, the irrigation technique, leakage of the piping system, or other poor management practices (Howell, 2003). The irrigation efficiency in % can be calculated as presented in equation 13.

Equation 13: Irrigation Efficiency

$$irrigation\ efficiency = \left(\frac{net\ irrigation}{gross\ irrigation}\right) * 100$$

Gross irrigation

The water, expressed in mm depth, that is discharged to irrigate a field is defined as gross irrigation. Accordingly, the gross irrigation is an empirical value.

Net irrigation

Calculated by multiplying the gross irrigation by the irrigation efficiency, the net irrigation indicates the water depth in mm that is effectively applied to the field.

Net Irrigation Losses

If the soil moisture content exceeds the field capacity, the irrigated water is presumed to be accounted as net irrigation losses through deep percolation. Therefore, the surplus fraction of water being applied in so-called over-irrigation can be estimated by utilizing the net irrigation losses [38].

Mixed Irrigation Systems

To controllably increase productivity and decrease the dependence on weather conditions, rain-fed agriculture is commonly complemented with man-made irrigation drawn from wells or rivers, powered by gravity or pumps, transported through canals, pipes, or hoses, and distributed via open ends or valves [12]. Combinations of rain- fed, and artificial irrigation are defined as mixed irrigation methods [39]. By applying the mixed irrigation approach higher yields and increased resistance are gained in comparison to purely rain-fed systems. However, exclusively irrigated and mixed systems demand energy, irrigation materials as well as the irrigation water itself. Exclusively artificially irrigated farms, like greenhouse systems, provide even higher control, resilience, and yield optimization on the one hand, but usually demand higher energy and water resources as well as materials, than mixed systems, on the other [3].

Categories of Irrigation Techniques

On a basic level, there are four different irrigation techniques. These are: subsurface irrigation, surface or gravity irrigation, trickle or drip irrigation, and fourthly sprinkler irrigation [36]. Subsequently, irrigation systems can further be categorized into sub-categories, as displayed in figure 6.

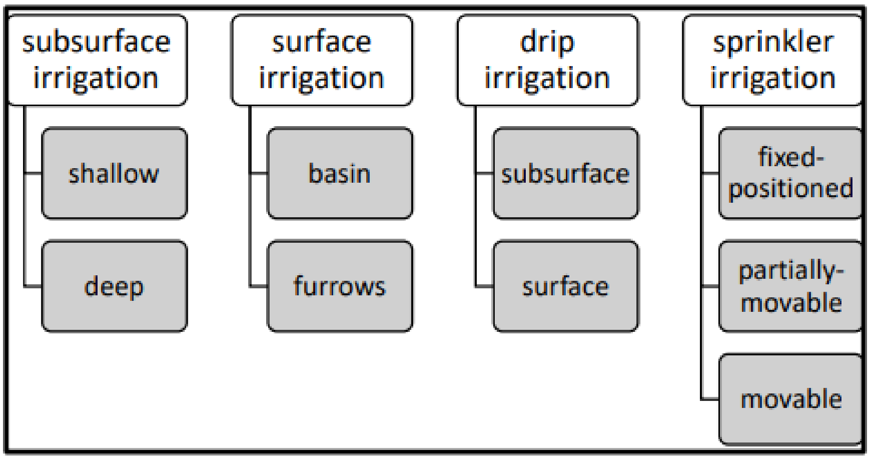

Figure 6: Categorization of irrigation techniques [36]

Literature Review

Comparison of Irrigation Systems

Table 1 allows to compare the main categories of irrigation systems regarding consciously selected parameters. It must be noted that the parameters depend on the crop, soil, system design, water quality, wind, temperature, and more. Therefore, the categorization into low, medium, and high should be seen as a general orientation [40].

Table 1: Comparison of Categorized Irrigation Technologies for Selected Parameters According to [40]

Irrigation categories	Irrigation water requirements	Water efficiency	Energy demand	Expected CapEx	Crop yield response	Expected OpEx
Surface	Low	Medium-High	Low-medium	Low	Low-medium	Low
Sub-surface	High	Low	Low-Medium	Medium-high	High	Medium-high
Sprinkler	Medium	Medium-high	Medium-high	Medium	Medium-high	Medium
Drip	High	Low	Medium-high	High	High	Medium-high

For the sake of this study, a detailed comparison of sprinkler systems is given in table 2 (Scherer, 2005). The compared parameters are the land covered by the sprinkler technique in %, the Capital Expenditure costs (CapEx), and the Operating Expenditure (OpEx), each in USD [$] per ha. On the one hand, the CapEx describes how much capital must be spent to install or realize a venture. The OpEx on the other, indicates how much costs can be expected to operate the venture during a set period.

Table 2: Comparison of Sprinkler Systems for Selected Parameters [41]

Sprinkler system	CapEx [$/ha]	OpEx [$/season/ha]
Center-Pivot	163	90
Pivot with Corner	170	91
Linear move	179	103
Big Gun	169	167
Side roll	140	145

As table 2 indicates, the different sprinkler technologies vary in both CapEx and OpEx. The estimations of the cost considered the costs for the pump and motor, the needed meters in pipes and number of valves and the costs of the irrigation machinery itself.

Materials and Methods

The methodology was designed to align with the objectives of the case study, the research question, the existing challenges, and an idea to tackle them. The thesis applies a approximative approach. The methodological tools employed aim to engineer a suitable irrigation scheme within the given limitations. This methodological framework is designed to be used for different processes like irrigation planning, improvement, or comparison. The case study´s irrigation scheme is developed by firstly analyzing the study site, secondly determining the net irrigation water demand, thirdly nailing down a feasible irrigation technique, and finally laying out and characterizing an irrigation scheme for the case study in detail.

Remote sensing analysis and diverse satellite datasets are processed in Web-GIS and QGIS to gain relevant information about the study site. The net irrigation demand is calculated by using the climatic data drawn from ClimWat and further on the various applications of the CropWat software. In combination with the requirements for the irrigation system is the previously reviewed literature used to select a suitable irrigation technique for the Bonosha farm. Subsequently, EPAnet is being used as a software tool to lay out different irrigation schemes and gain information about costs and energy efficiencies.

All software tools are open-access and freely provided by the corresponding institution. The processed datasets are leveraged by publicly available sources, like the FAO or NASA. Currently, there appears to be no explicit methodology for the engineering of river-based irrigation schemes in remote regions and data-scarce projects. Therefore, the thesis developed a methodological framework for this endeavor. While broadly fenced in scope, this methodology could entail a high practical usability for an agricultural venture, due to its low application barriers.

Detailed explanations about the data, processes and software application used in the methodological framework of this thesis are visualized in figure 7.

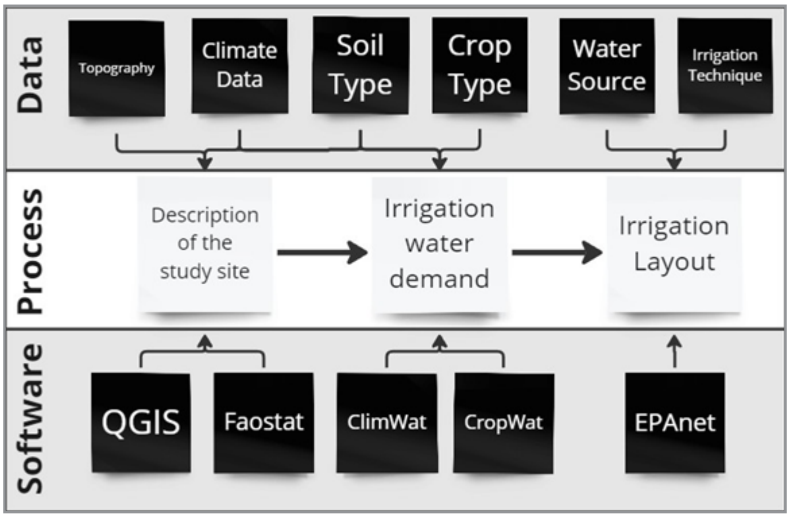

Figure 7: Methodological framework for engineering a river-based irrigation scheme

Hand-in-Hand Geospatial Platform

The Hand-in-Hand (HiH) geospatial platform is openly accessible and provided by the FAO. The HiH platform combines data from various sources, research studies, as well as organizations and enterprises. This allows stakeholders to easily access diverse information for their required needs [22]. The FAOSTAT datasets for example include data on food and agriculture for 245 countries over a time span of up to 60 yearsv [42]. 65 countries, among them, Ethiopia, officially participated in the development of the HiH technology and the leveraging and contribution of relevant datasets [43].

On behalf of this thesis, selectively chosen information about the study site was directly sourced from the HiH platform. In addition, the raw data sources were evaluated and partially further analyzed in the GIS-Software QGIS 3.28.

QGIS

QGIS is a free and open-source geographic information software, which can be used to edit, analyze, and present data and data relations [44]. The study will use the latest stable QGIS Version 3.28 to outline and calculate the study area, create a DEM (digital elevation model) of the study site, and visualize information like administrative boundaries or rivers and water bodies.
The coordinate reference system (CRS) is set to WGS 84 / UTM zone 37N (Authority ID: EPSG: 32637). OSM (Open Street Map) is added as a background layer [45]. The X and Y coordinates of the study site are integrated as point data, connected by lines, and polygonised accordingly. The GPS-coordinates of the Bonosha farm can be found in the appendix 2. The study area is calculated using the QGIS field calculator.

For the creation of the DEM contour model, the SRTM 3.2.0 Plug-In in QGIS is being used, accessing the dataset from NASA's Earthdata platform [46]. In the following, the DEM was clipped to the farm outline, and then, to improve clearance, smoothed, and labeled with contour lines of 2m distance. Data about the rivers of Africa was implemented in the GIS, to portray the flow path of the Bilate River [47]. Further on, the QGIS file provides a background map and partial data foundation for the irrigation system layout and characterization via EPAnet.

ClimWat

The FAO software ClimWat Version 2.0 is being used to leverage monthly climatic data with a historical timespan of minimum 15 years [48]. A minimal time span of 15 years is chosen to be representative for historical observations. If data from a longer time span is available, it is being utilized. The weather station Alaba-Kolito (Longitude 38.1°, Latitude 7.36°, Altitude 1850m) is being selected. ClimWat 2.0 was chosen due to its integrative compatibility with the software tool CropWat 8.0.

CropWat

CropWat Version 8.0 is a support tool for agricultural decision-making, developed by the FAO [35].

The ClimWat data is integrated into CropWat. To estimate the ET_0, the Penman-Monteith method is applied (Equation 1). According to the insights from Bokke et. al, the USDA-SC method was selected to calculate the effective rainfall [30]. For the crop data, the category "small vegetables" from the CropWat database is selected, estimating that the crops of the project show similar characteristics. Medium loam is selected as a soil type, as it is assumed that the soil type of the study site, is best represented by this selection. Due to the defaults of the case study, the crop pattern in CropWat is set to three growing cycles, each with a coverage of 100% of the total farming area. The yield reduction factor is set to 0%.

EPAnet

With the software program EPAnet, developed by the U.S. Environmental Protection Agency, the hydraulic behavior in a pressurized pipe network can be simulated [49].

The hydraulic settings of EPAnet 2.2 are set to the metric system. As a headloss formula the Darcy-Weissbach equation is applied. Pipes roughness is set to 0.03mm, which is equal to the epsilon of the Darcy-Weissbach equation. Further settings are set by default according to the user manual [50]. The dimensions of the EPAnet file are set to the boundaries of the previously extracted QGIS map extension.

To initially lay out the irrigation network, the QGIS file, including the DEM and measurements of the farm, was integrated as a backdrop. Additionally, the location of the sprinkler guns was integrated into EPAnet. The backdrop layer enabled the precise layout of the network. Thereafter, the sprinklers, the reservoir, and the corresponding element characteristics were set. The reservoir and sprinklers were connected via pipe and pump elements. The element characteristics of the pipes were set. A pumping pattern was developed and assigned to the pump.

Following, a simulation analysis, over 48 hours, was performed. Accruing errors were fixed, and results were analyzed and noted down. The settings for the element characteristics were iterated out to optimize the simulation outcome, regarding pressure levels and material demand.

Results and Discussion

The results and discussions of this thesis have to be considered along the mentioned limitations of the study. In particular, data scarcity influenced the level of detail regarding the results. Therefore, the presented results should be seen as approximations of the reality. The needed steps, analysis, and methods to improve the results are discussed in this chapter, to enable the interested reader to perform them accordingly.

Throughout this chapter, the research questions of what parameters are mandatory for the planning of an irrigation scheme and how they can be considered in data-scarce project environments are answered.

In addition, the given objectives for the irrigation scheme will be addressed and assessed. As stated in section 1.2.1, the objectives are - to firstly provide irrigation consistently throughout the year, secondly to be suitable for river water with high sediment containment, thirdly to be water and energy efficient, and fourthly to be cost-efficient in CapEx and OpEx.

This section starts by describing the study site, then presenting the crop data, and the selection of the irrigation system, which includes mentioning parameters that are mandatory for the effective design of a scheme. Ultimately, a suitable irrigation layout and its characteristics for the case study are proposed.

Analysis of the Study Site

The study area is administrated as a part of the Shashoga Woreda, which is a Woreda of the Hadiya Zone in the SNNPR region of Ethiopia. A Woreda is an administrative zone, similar to a district or county. The administrative zones are represented in figure 8, scaling down from figure 8.1 to figure 8.4.

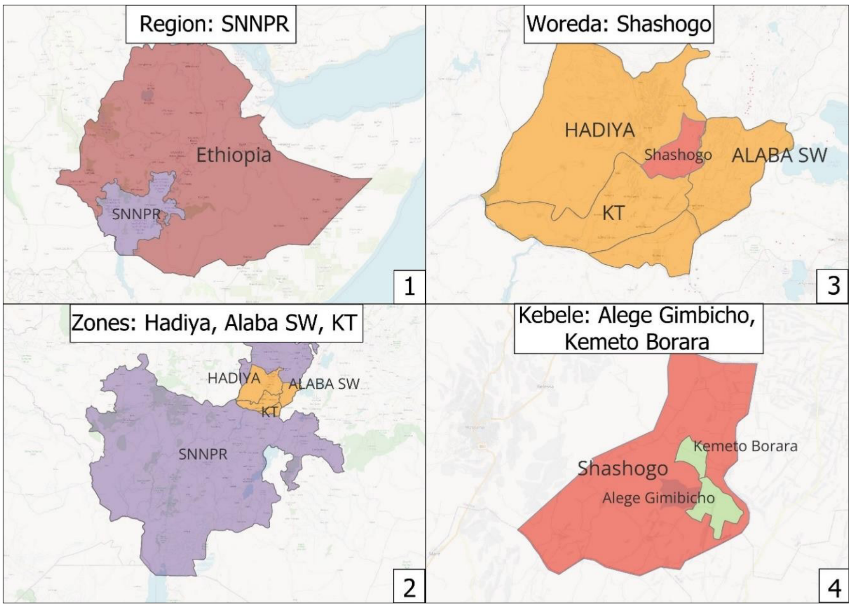

Figure 8: 1-4 Administrative zones of the study site (extracted out of QGIS)

Due to current political and territorial conflicts throughout different regions in Ethiopia, the indicated borders of the administrative zones must be seen as the status quo, that may change in the future [51].

The administrative zones are influencing the case study in multiple ways. For example, they impact the availability of government funding and substitutions, water, and agricultural rights, or land ownership agreements.

The farm borders the Kebele Alege Gimbicho in the southeast and the Kebele Kemeto Borara from the South to the North along the eastern side of the farm (Figure 9). A Kebele is an administrative zone, similar to a sub-district or neighborhood. For the farmland itself, there is no official Kebele assigned. It is highly likely that the administrative setting for the farmland is clarified throughout the different political stakeholders of the region. However, within the scope of this study, of using remote sensing technology and public data, this could not be determined.

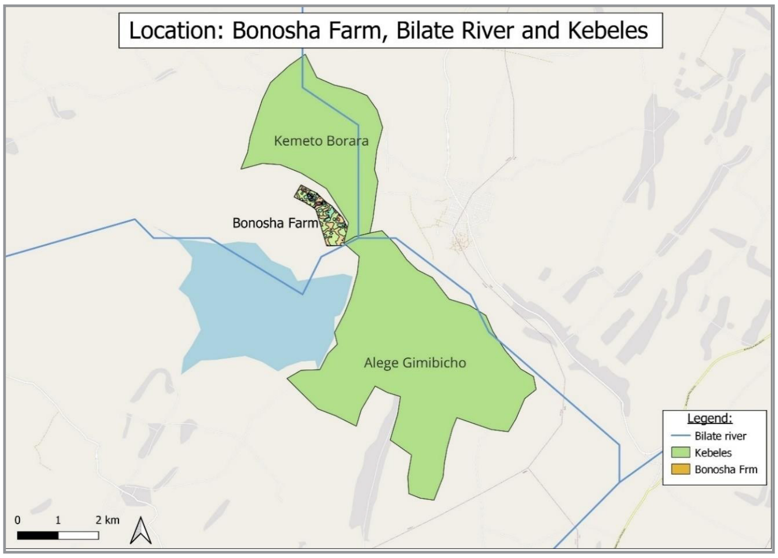

Figure 9: Location of the Bonosha farm (extracted out of QGIS)

Digital Elevation Model

The Bonosha farm is located in the north of the Rift Valley Basin (395836.7°-397189.6°N, 830363.7°-829161.1°E). The total area of the farm is 84.74 ha with an altitude of about 1885m up to 1900m. As shown in figure 10, the south of the study area borders the crossing of the Bilate river. The two streams join at the intersection and continue further south, as the Bilate River, towards the lake Abaya.

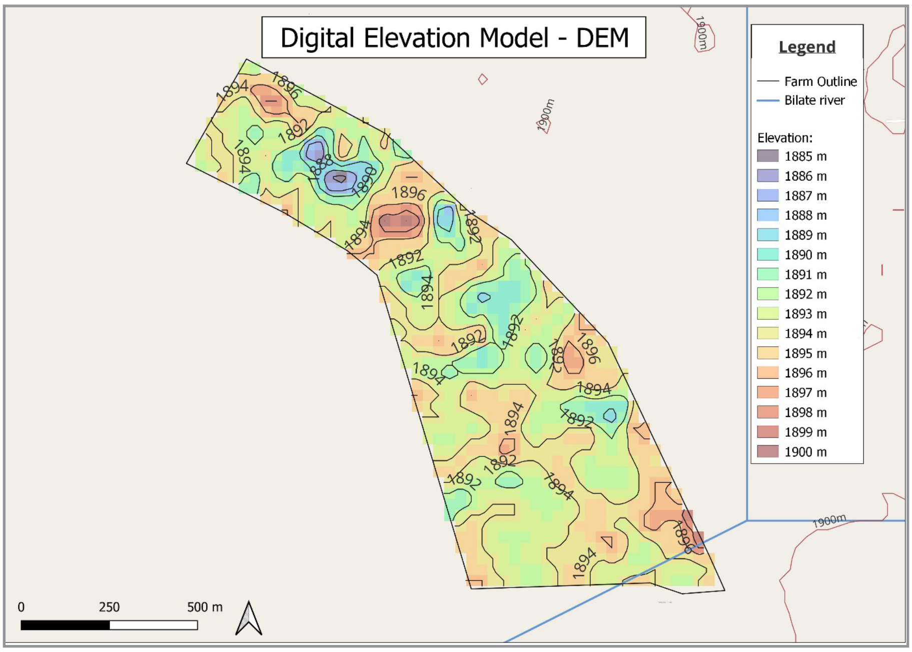

Figure 10: Shows the digital elevation model (DEM) for the study site.

It can be expected that land leveling will take place on the study site and therefore make the farm more suitable for conventional irrigation and farming. Otherwise, alternative farming, irrigation techniques, and concepts could make use of the natural topography, for example by using the given sink at the northern part of the farm as a natural water storage for rainwater harvesting. Even if the awareness of the slopes and topography of the study site is presented and needs to be further considered in the practical implementation, it will not be considered for the drafting of an irrigation system in this thesis.

The DEM as well as the administrative boundaries and the location of the farm can be found in the attached QGIS-file (Appendix 3 and appendix 4).

Climate Data

Country: Ethiopia   Station: ALABA-KOLITO

Altitude: 1850 m.   Latitude: 7.36 °N   Longitude: 38.10 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	10.8	27.6	57	78	8.1	19.8	3.80
February	12.1	28.1	54	78	8.2	21.1	4.17
March	12.3	27.7	59	78	8.5	22.6	4.43
April	12.9	27.0	63	78	8.1	21.9	4.31
May	12.0	26.9	74	78	7.6	20.6	4.00
June	12.3	25.3	75	95	6.5	18.5	3.62
July	12.8	23.5	78	52	5.3	16.9	3.18
August	12.6	23.8	77	35	5.4	17.5	3.23
September	12.5	25.1	77	69	5.2	17.4	3.37
October	10.5	26.6	71	69	8.2	21.2	3.96
November	9.2	27.1	58	86	8.8	21.0	4.01
December	7.9	27.8	53	86	8.3	19.7	3.82
Average	**11.5**	**26.4**	**66**	**73**	**7.3**	**19.8**	**3.83**

Figure 11: Climate data from the weather station Alaba-Kolito [35]

Figure 11 displays the historical climatic data that was chosen to represent the climatic circumstances at the study site. It is to be mentioned that the weather station Alaba-Kolito, where the climatic data was measured, is in 21.92 km distance to the study site and shows, with 1850m compared to the average 1894m elevation of the study site, a delta in elevation of 45m. However, the shown data should be seen as the best available estimation, even if it is not as an actual representation of the study site´s climate [52].

It can be assumed that the minimum, average and maximum temperature at the farm slightly differ from those at the weather station due to the delta in elevation. The weather station´s values for "Humidity", "Wind", and "Sun", are assumed to match the circumstances at the study site accurately.

As visualized by the graph in figure 12 the ETo, calculated by using the Penman-Monteith method, peaks at 4.43 mm/day in March and is at its low (3.18 mm/day) in July. The ETo (Y-Axis) shows maximum fluctuations of 1,25 mm/day throughout the months (X-Axis).

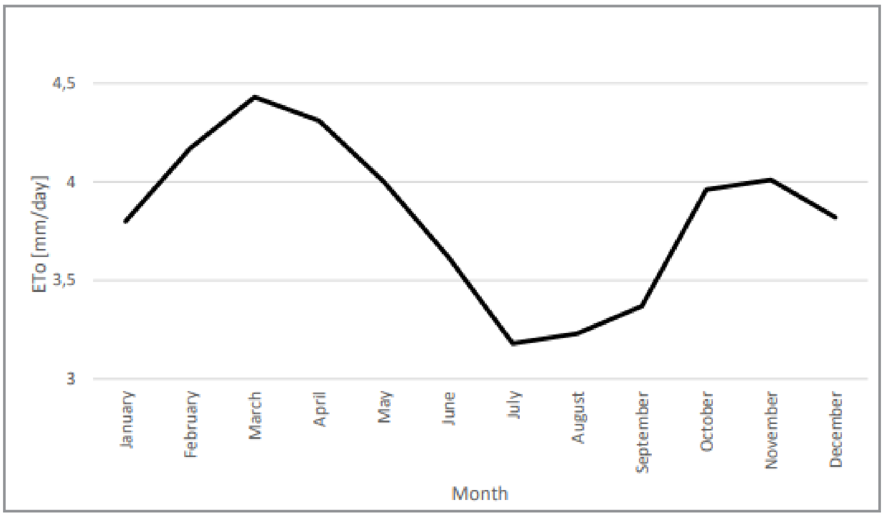

Figure 12: Development of ETo at the weather station Alaba-Kolito [35]

Further on, the utilization of the ETo can be discussed, caused by the fact, that ETo is estimated using a reference soil and not the actual soil(s) of the study site [29]. Performing experiments to calculate the actual evapotranspiration using soil samples from the study site would be expected to enhance the significance of the evapotranspiration data.

Rain Data

Figure 13 displays historical values for the rain and the effective rain at the weather station Alaba-Kolito. To estimate the effective rain, the FAO/AGLW formula was applied. Out of the total rainfall of 970mm per year, 81,34% take place in the seven months from February to May and July to September. In between those rain seasons the historical data indicates a decrease in rain intensity or even a break of the rain season in June, where just 64mm of average rain is measured.

With an effective rainfall of 528.8mm, only 54.5% of the total rainfall is available for crop growth. In April, July, and August the raining efficiency is above 60% and in November, December, and January below 30%. This reflects, that the efficiency of rainfall is high, when the amount of rain is high, and that the rain efficiency is low, when the total amount of rain is low. Further this can be explained, because the rain losses through evaporation are lower during constant or regular raining events.

Station ALABA-KOLITO   Eff. rain method FAO/AGLW formula

	Rain	Eff rain
	mm	mm
January	32.0	9.2
February	89.0	47.2
March	98.0	54.4
April	124.0	75.2
May	107.0	61.6
June	64.0	28.4
July	131.0	80.8
August	128.0	78.4
September	112.0	65.6
October	48.0	18.8
November	32.0	9.2
December	5.0	0.0
Total	970.0	528.8

Figure 13: Rainfall and effective rainfall at the weather station Alaba-Kolito [35]

The amount of precipitation and the developed rainfall pattern in figure 14, are assumed to be representative of the study site, according to the figure 13.

The grey graph displays the effective rainfall, the black graph displays the total rainfall. The X-Axis indicates the month, from January to December. The Y-Axis displays the amount of precipitation in mm, from 0 mm to 140 mm [53].

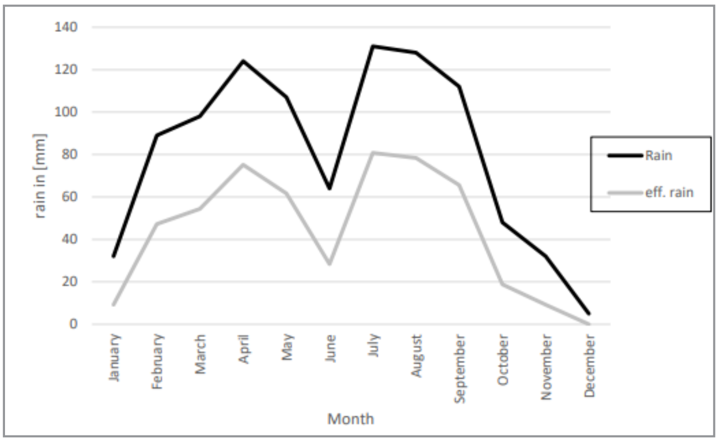

Figure 14: Development of rainfall and effective rainfall at the weather station Alaba-Kolito [15]

The rain season from June to September is locally known as Kiremt. However, the graphs, indicate that there are two rainy seasons over the historical observation of available data. The second rain season, reaching from February until May, started to evolve over the last two decades and is probably due to climate change and accompanying changes in the global water circuit. In southeast Ethiopia, where two rain seasons are already common, albeit with less intensity, people and agriculture historically adapted to those climatic circumstances [54]. The irrigation demand estimated in this thesis is adjusted to the rain data shown in figure 14. In addition, it is advised to further consider rain prognosing models and simulations in planning processes and look for best-practice adaptations in agriculture from other regions among Ethiopia and their neighboring countries. Furthermore, empirical data is accounted to have a higher resolution and significance and could therefore provide a more realistic representation of the climatic circumstances influencing the study site.

Soil Data

Even though the dominant soil type could be identified as Andosol via remote sensing, the explicit soil data, such as the field capacity, or sand, clay, and silt proportions could not be estimated. Typically, this information about the soil is gained through experiments, however, the limitations of this study are restricting those methods [34]. Therefore, the values shown in figure 15, are drawn from a dataset of FAO. Figure 15 shows information about the soil, which is further used to estimate the irrigation water demand.

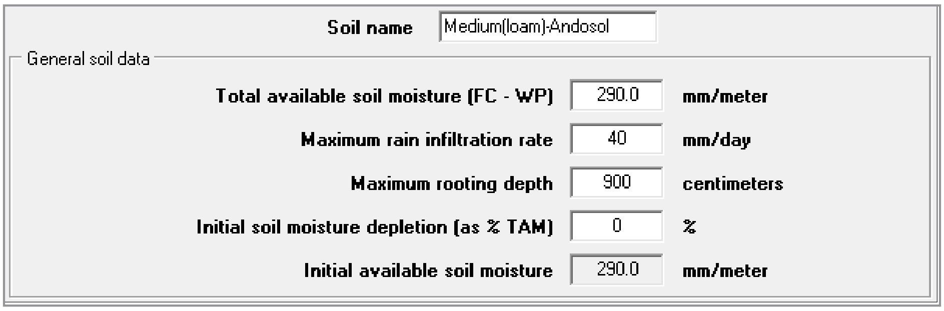

Figure 15: Soil data used in CropWat for medium loam – Andosol [35]

The additional information about the soil, gained through remote sensing, is listed in table 3. While the primary and secondary soil type, as well as the top-, and subsoil pH, do not find application in this thesis, it is crucial to know that the soil is predicted to be workable, non- toxic, and shows a rooting depth of minimum 100cm. Especially the assumptions about the toxicities should be proven by analyzing field samples.

Table 3: Additional soil data for the study site (FAOSTAT, 2024)

Parameter:	Value:	Unit:
Primary soil type	Andosol An	-
Secondary soil type	Vertisol Vr	-
Topsoil pH	6.9	-
Subsoil pH	7.5	-
Soil reference depth	100	cm

Crop Data

The dataset, representing the characteristics of the planned crops, displays a total duration of 95 days for one growing cycle (Figure 16). It is shown that the yield response of the crops varies, depending on the corresponding growing stage. This is expressed by the unitless yield response factor which varies from 0.4 in the development stage, up to 1.2 in the mid-season stage. The maximum rooting depth for the selected crop is 60cm and the crop height peaks at 30cm. The Kc value starts at 0.7, peaks at 1.05, and ends at 0.95 linearly influencing the ETc. The planting date and the date of harvest can be set to satisfy individual requirements.

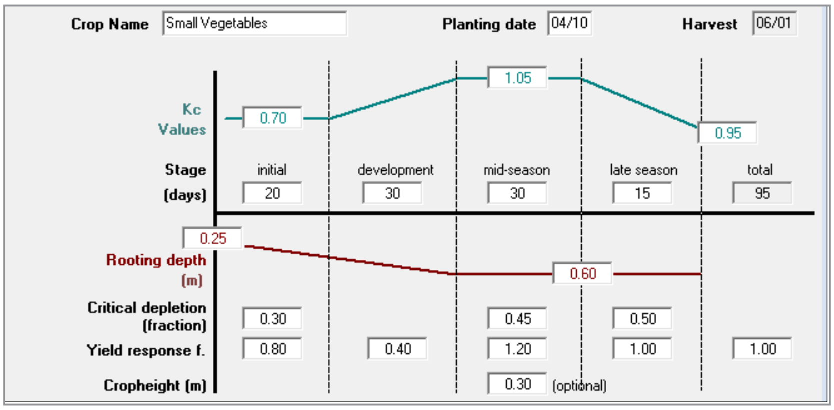

Figure 16: Crop data for small vegetables divided into growing stages (extracted out of CropWat 2023)

As explained in the methodology section, the presented dataset aims to represent the planned crops of the Bonosha farm. However, because multiple crops are planned to be planted, and it can additionally be assumed that they will differ from the according reference crop type due to crop variety, the usage of the reference crop group in this thesis does not holistically represent the complexity of the crop parameters [29]. The significance of the presented crop data can therefore be improved by estimating the values by experiment.

Crop Pattern

The crop pattern is set as shown in figure 17. With a duration of 95 days per growing cycle, a pattern of 3 cycles per year is suitable. This pattern also allows for an additional 80 days per year where no crop is planted, grown, or harvested. These additional days could be set strategically in between the growing cycles in dry or rainy seasons, where yield is expected to be low or when sensitivity is high and resilience low while yield losses are likely to occur. The additional 80 days are commended to be used for land rehabilitation, land and machinery preparation, irrigation system repairs, and more.

Cropping pattern name: 3_vgtbl_extra_time

No.	Crop file	Crop name	Planting date	Harvest date
1.	...CROPWAT\data\crops\FAO\VEGETABL.CRO	Small Vegetables	01/01	05/04
2.	...CROPWAT\data\crops\FAO\VEGETABL.CRO	Small Vegetables	03/05	05/08
3.	...CROPWAT\data\crops\FAO\VEGETABL.CRO	Small Vegetables	03/09	06/12

Figure 17: Potential planting and harvesting dates for 3 growing cycles per year [35]

Crop Schedule

To gain deeper insights, figure 18 shows the development of Kc, ETc, Eff. Rain and irrigation required per monthly third. This analysis allows to preset the flow in the irrigation system according to the corresponding decade. However, in practical usage, the flow should be controlled according to the weather- and climatic conditions that occur in field [3].

ETo station: ALABA-KOLITO | Crop: Small Vegetables

Rain station: ALABA-KOLITO | Planting date: 04/10

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Oct	1	Init	0.70	2.64	18.5	7.2	13.3
Oct	2	Init	0.70	2.77	27.7	4.5	23.2
Oct	3	Deve	0.74	2.94	32.4	4.0	28.3
Nov	1	Deve	0.86	3.44	34.4	4.1	30.3
Nov	2	Deve	0.98	3.94	39.4	3.1	36.3
Nov	3	Mid	1.06	4.18	41.8	2.0	39.8
Dec	1	Mid	1.06	4.12	41.2	0.1	41.1
Dec	2	Mid	1.06	4.05	40.5	0.0	40.5
Dec	3	Late	1.03	3.94	43.3	0.1	43.2
Jan	1	Late	0.97	3.71	22.2	0.7	21.7
					341.5	**25.8**	**317.8**

Figure 18: Kc, ETc, Peff and Irrigation requirement of the case study per monthly third for the growing cycle from October till January [35]

The individual planting date(s) and therefore the as well the dates of the growing stages, can be set in the CropWat file in the appendix 5. The presented values will adapt accordingly.

Irrigation System

The selected irrigation technique for the Bonosha farm is irrigation via fixed-positioned center-pivot sprinkler guns. The selection is due to the criteria mentioned in tables 1 and 2. Because the water for the Bilate River, which is used for irrigation, is unknown in its containments, especially in particle count and size, robust characteristics for the irrigation system are required. This is as well required by the objectives for the irrigation scheme number one and two.

Water containing high amounts or larger-sized particles can cause clogging of the nozzles and the piping system. The fine nozzles of drip irrigation techniques would be assumed to clog regularly when using river water for irrigation. This restriction in technical viability, due to particle size, excludes drip irrigation systems as viable options for the case study. Even though drip irrigation techniques typically show high water efficiencies and good controllability. If water analysis indicates that drip irrigation is viable for the case study, it is expected to display a viable alternative to the proposed irrigation scheme.

Surface irrigation techniques have an average water efficiency of 70% compared to the 90% average water efficiency for sprinkler systems. This is since surface irrigation is characterized by high proportions of evaporation, which results in a reduced water efficiency. In addition, it has to be noted that surface irrigation is mostly driven by gravitation, which is energy efficient on the one hand but requires the land to have a constant minimum slope throughout the whole irrigated area, on the other. This is currently not given at the terrain of the Bonosha farm. Furthermore, surface irrigation through canals and furrows potentially provides breeding spaces for mosquitos, decreases resilience through flooding, and can easily lead to over or underirrigation since it can be challenging to dynamically control the amount of irrigation water reaching the crops.

As the thesis displayed, the benefits of the fixed-positioned center-pivot sprinkler gun, in comparison to other sprinkler irrigation techniques, are the low investment costs, as well as the low demand in manpower for operation, and the high resilience of the system due to fixed installed pipes, sprinklers, and potential pumps.

The principles presented in this section, firstly excluding drip and surface irrigation techniques, and secondly comparing sprinkler systems, led to the selection of irrigation via center-pivot sprinkler guns. With this choice of irrigation system, the objectives set by the project partners are expected to be satisfied.

Irrigation Scheme Supply and Schedule

Figure 19 provides an overview of the scheme supply and includes the maximum net irrigation water requirement (0.45 l/s/ha), which is used to further used to layout the irrigation system with EPAnet. The maximum net irrigation water demand is being used for further calculation, as the system dimensions should be designed for the maximum load.

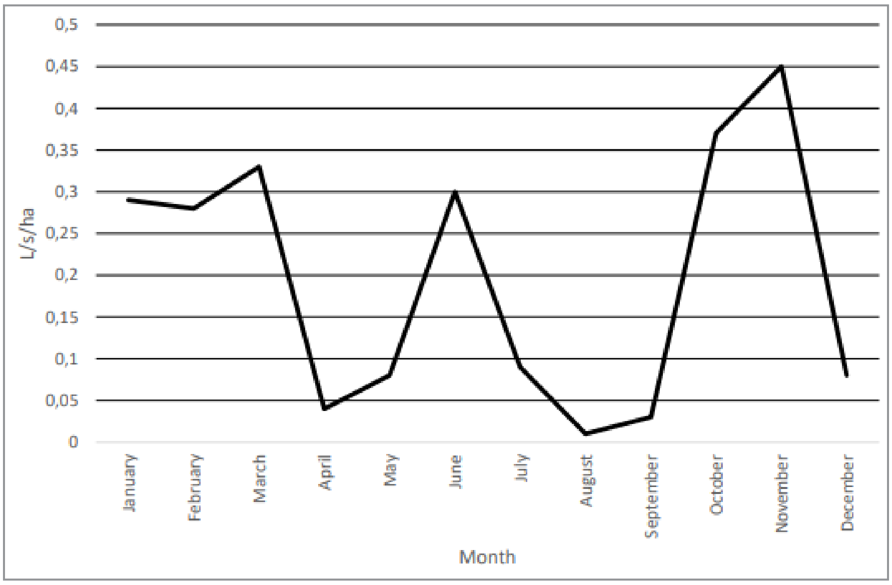

Figure 19: Net irrigation water requirement [l/s/ha] of the Bonosha [35]

The irrigation of the farm can be scheduled in different manners. The easiest one to operate is to irrigate over 24 hours per day continuously with constant flow and pressure levels. To increase water and energy efficiency and the longevity of the machinery and irrigation equipment, it is recommended to irrigate according to climatic parameters, especially temperature conditions. For instance, to irrigate 18 hours daily, with a break during the midday from 11 am to 5 pm. Irrigating during the colder hours of the day will reduce the losses through evaporation and will increase water and energy efficiency accordingly. However, if a solar pump is used to irrigate, the midday hours can be seen as attractive irrigation hours due to higher solar radiation and with-it energy supply. For fuel or wind- powered pumps, this is not the case [37]. The irrigation scheme of this thesis is accordingly being simulated for a 16-hour time period.

Irrigation Scheme Layout

For the drafting of the irrigation scheme layout, shown in figure 20, the center pivot sprinkler technology was selected. The commonly commercially available radius for sprinkler guns of 400m was assumed, as it can be seen as the most likely installed version.

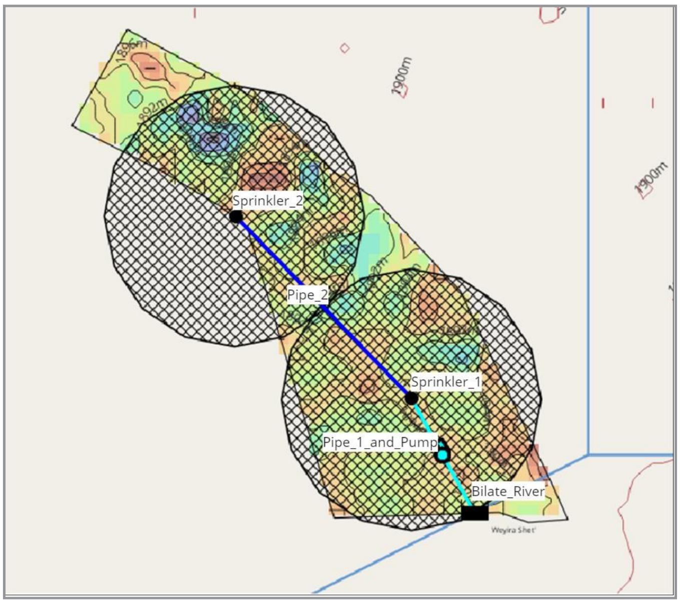

Figure 20: Layout of the proposed center pivot sprinkler irrigation scheme of the Bonosha farm [49]

Results and Discussion

The network layout can be viewed in detail in appendix 6.

Two locations for the center pivot sprinkler guns were chosen. The selection of the locations was done by hand, seeking to optimize the irrigation coverage by the sprinklers. The land covered by the irrigation of each sprinkler is indicated by the crossed-lined circle in figure 20. With these locations of the sprinkler guns, a total land coverage of 81.87% can be achieved. This translates to 67.99 ha out of the 83.04 ha total farming area. To achieve full irrigation coverage, additional irrigation systems in the form of center pivot guns with smaller radii, can be used. However, this was not further analyzed in this study. As figure 20 indicates, both sprinklers do not only cover farming land, but non-farming land outside of the case study site too. For sprinkler one, this is neglectable since it is just a small proportion of the total land covered by the sprinkler. However, for sprinkler gun two, the setting should be set to rotating within 240° to minimize the wastage of irrigation on non-farming land and enhance water and energy efficiency. Furthermore, it should be noted that wind speed and direction will influence irrigation and equal distribution throughout the land. Depending on the influences due to wind, a relocation or rotation adjustment of the sprinkler guns may be recommendable [12, 41].

To ensure a high resilience of the irrigation scheme, the simplest possible piping system was chosen. In this system, the reservoir is connected via pipe and pump to sprinkler number one while sprinkler number two is linked up by another pipe.

Irrigation Scheme Characteristics

The elements of the presented irrigation scheme show the characteristics that are displayed in the following tables 4 - 8. Appendix 6 includes the presented irrigation scheme layout, as well as element characteristics plus additional information that is not included in this thesis. The shown element characteristics are set or simulated via the EPAnet-software. The actual product characteristics applied in the case study differ from those presented in the following tables. Therefore, the presented values should be seen as guidance, enabling an informed choice for the decisions to be made in the case study. To increase the model´s significance, the values that are set for each element in EPAnet should be adapted towards the chosen product characteristics [50].

Table 4 indicates the characteristics of the Bilate River, which is symbolized by the reservoir element in the EPAnet-file. The net withdrawal per second is around 30.59 liters. This is equal to the total irrigation demand of the irrigated farm area. The set elevation for the Bilate River, which is being used in the simulation process for estimating the pressure levels, is 1895 meters. It should be noted that the water level of the river underlies fluctuations, assumingly of multiple meters. These fluctuations will influence the total pressure head of the scheme. When the water gauge is low, the demand for energy to pump the water to the sprinklers will increase. If the water gauge is high, the demand will decrease accordingly [55]. Approaches utilizing historical observations, empirical data, or prognostic simulations about the fluctuations of the river level could increase the model's significance. The gained data could be included in the reservoir-element characteristics in the EPAnet-file. Further, the expected fluctuations of the river level impede an accumulation of river water in a separate reservoir, otherwise, this could present an appealing solution to decrease the energy demand of the scheme [56].

Table 4: Coordinates and net outflow of the Bilate river at the Bonosha farm

Element	X-Coordinate	Y-Coordinate	Elevation [m]	Net Outflow [L/s]
Reservoir Bilate River	838174.454	4237811.296	1895	30.59

Table 5 provides information about the characteristics of the sprinklers being used in the center pivot irrigation layout. Besides the location, the covered farm area, and the base demand for each sprinkler, the pressure head is mentioned. The elevation of both sprinklers is at 1895m. The pressure head, equivalent to the available pressure at the sprinkler nozzle, must be within the range of the operating pressure of the selected sprinkler version. These ranges in operating pressure can typically be looked after in the product manual. If the pressure head at the sprinklers may be too low, the pressure generated by the pump, or the pipe diameter could be increased. To optimize energy and resource efficiency the presented pressure head is chosen to be suitable for commonly used sprinkler guns [50]. Because the pressure, to firstly transport the water to the sprinkler, and secondly to operate them, demands most of the scheme's energy, and therefore most of the OpEx, it is recommended to observe, iterate, and further optimize the pressure settings at the sprinklers and the pump.

Table 5: Coordinates and Element Characteristics of the Sprinkler Guns

Element	X-Coordinate	Y-Coordinate	Covered farm area [ha]	Base demand [L/s]	Total Head [m]	Pressure Head [m]
Sprinkler 1	838060.535	4238020.201	41.68	18.757	1965.45	70.45
Sprinkler 2	837740.239	4238351.113	26.31	11.838	1910.36	15.36

The characteristics of the pipes are shown in table 6. The roughness coefficient of the pipes is assumed with 100mm. This value can be improved by using empirical data and the Darcy- Weissbach equation [57]. The fluid velocity can further be utilized to estimate the forces emerging within the pipe, as well as the ones potentially emerging at bearings and knots. The headloss accruing in the piping system is mainly due to friction and the pipes' dimensions. Therefore, an assumption can be made that headloss can be reduced by decreasing the roughness of the piping material or the dimensions of the pipe. It must be taken into consideration that the piping length, presented in table 6, represents a theoretical value. As a safety margin, more piping material should be ordered, as it is likely to be required, for example, due to an increasing demand through bypassing rough terrain or storage and transportation damage [25].

Table 6: Element characteristics of the pipes

Element	Length [m]	Diameter [mm]	Roughness Coeff. [mm]	Flow [L/s]	Velocity [m/s]	Unit
Headloss [m]	838060.535	4238020.201	41.68	18.757	1965.45	70.45
Pipe_1	400	200	100	30.59	0.97	79.99
Pipe_2	800	150	100	11.84	0.67	68.86

As shown in table 7 the pump of the irrigation layout presented in figure 20, runs with a headloss of -102.45 meters. Accordingly, the required pressure head of the pump is 102.45 meters. The average efficiency of 75% is drawn from literature and the utilization of 70.83% results through the simulation in EPAnet. The efficiencies, alike the KWh/m³, strongly rely on the specific characteristics of the pump that will be implemented in the case study.

Table 7: Element Characteristics of the Pump

Element	Flow [L/s]	Headloss [m]	Average efficiency [%]	Utilization [%]	KWh/m³
Pump	30.59	-102.45	75	70.83	40.97

Table 8: Shows the total area of the study site, the irrigation coverage with the presented center pivot irrigation scheme, and the assumed CapEx and OpEx for the irrigation scheme.

Table 8: Estimated costs of the center pivot irrigation scheme at Bonosha farm

Sprinkler system	Total area [ha]	Irrigation coverage [ha]	Assumed CapEx [$]	Assumed OpEx [$/season]
Center Pivot	83.04	67.99	11082	6119

The calculations of table 8 are according to table 2. The presented values will enable decision-makers to estimate the economic viability of the presented irrigation layout. As the needed capital investment, as well as the operational expenses, heavily depend on the market prices, the given values should be seen as approximations. Further information can be found in the appendix 6 [58, 59].

Conclusion

The thesis started by framing the research design, introducing the case study, and subsequently the relevance and limitations of the study. Afterwards relevant applied concepts, parameters, and equations were explained. The used software tools and data sources were mentioned before the results and their discussion took place. In a nutshell, the thesis demonstrated how to estimate the irrigation water demand and develop an irrigation schedule and layout accordingly.

The first research question: What parameters ought to be mandatory for the planning of an irrigation scheme? - could be answered. The thesis showed that the mandatory parameters for engineering an irrigation scheme are: the climatic conditions, the soil type and characteristics, the irrigation water demand, and the crop type and pattern. Moreover, influences such as the topography of the farming site, or further individual restrictions and objectives must be taken into consideration, even though it can be challenging to account them.

The second research question: How can the individual context be considered in irrigation planning, especially when data and financial capacities are scarce? – were answered by the thesis, with the demonstrative engineering of an irrigation scheme under those restrictive circumstances. Data scarcity and limited financial capacitates in irrigation planning can partially be coped with by utilizing public data sources and open-access software. The thesis leveraged publicly available datasets and processed them via the open- access software tools, QGIS, ClimWat, CropWat, and EPAnet. In addition, the irrigation planning of the case study was exclusively performed remotely, adding another dimension to the independence from possibly existing limitations.

Regarding the case study, the thesis on the one hand found, that the land of the Bonosha farm is highly suitable for agriculture, characterized by an appealing soil type, the Andosol, and favorable climatic conditions. However, on the other hand, the thesis claimed that the available database regarding the specific environmental circumstances and the information about the water source, the Bilate River, are so scarce, that they are inhibiting further assessments and impeding the holistic engineering of an irrigation scheme.

As for now, three crop growing cycles per year, each of 95 days duration of small, highly valuable vegetables were recommended for the case study. Even letting a surplus of an additional 80 days per year. The fixed center pivot sprinkler gun, with a 400m radius, was stated as a highly viable irrigation technique for the farm. Following the proposed layout, it was estimated to irrigate 67.99 ha with 2 sprinklers and an associated CapEx of 11082 $ and a seasonal OpEx of 6119 $.

Therefore, the proposed irrigation scheme matches the set objectives. Firstly, the system is designed in a resilient manner, assumingly working reliably throughout the year. The irrigation layout is expected to withhold the applied pressure levels and potential weak spots were minimized. Secondly, the selected irrigation technique is suitable for river water, even when containing larger-sized particles and sediment. Thirdly, the thesis optimized the estimated water and energy demand, while considering the given project framework and further suggested ways to optimize resource efficiencies in the future. Lastly, estimations about the expected costs were made and can further be compared to other irrigation layouts. Leaving the fourth objective of cost efficiency open for an informed discourse.

In total, the thesis demonstrated a framework for remotely engineering a river-based irrigation scheme, that can easily be applied and reproduced, even when data and financial capacities are scarce.

Outlook

To validate the thesis findings and finalize the irrigation planning of the Bonosha farm, future data leverage is strongly recommended. This includes empiric analysis, especially regarding the crop, as well as the soil characteristics. In addition, information about the seasonal fluctuations of the Bilate Rivers gauge and its water quality are mandatory for an in-depth assessment and should therefore be performed.

Future research could analyze the effects of different crop types and rotation patterns or compare the characteristics of multiple irrigation layouts in regard to energy, water, or crop yield efficiency. Furthermore, the elaboration of the used machinery and materials, like pumps and sprinklers, presents an interesting endeavor.

The presented framework of engineering an irrigation scheme could be applied to ancillary case studies. A collaborative undertaking could evaluate, optimize, and supplement the thesis's framework further. This could improve the engineering of irrigation schemes in data and financially scarce project environments and therefore increase the empowerment of farmers, students, and organizations.

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List of Abbreviations

Abbreviation	Definition	Short explanation
GDP	Gross Domestic Product	Measure of a country's economic performance.
FAO	Food and Agriculture Organization	Specialized agency of the United Nations.
SNNPR	Southern Nations, Nationalities, and People's Region	Administrative region in Ethiopia.
GCC	Gulf Cooperation Council	Political and economic alliance of Arab states.
EU	European Union	Political and economic union of European countries.
CAPEX	Capital Expenditure	Spending on acquiring or maintaining fixed assets.
OPEX	Operational Expenditure	Day-to-day expenses for running a business.
NGO	Non-Governmental Organization	Non-profit organization, independent of government.
AGP	Agricultural Growth Program	Initiative aimed at fostering agricultural growth.
NASA	National Aeronautics and Space Administration	United States government agency for space exploration.

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