Land suitability evaluation for agriculture: development of an universal approach based on the case of the Blue Nile Basin

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Richard Jan Michael Gramlich

Berichter: Univ.-Prof. Dr.-Ing. Heribert Nacken
Univ.-Prof. Dr.-Ing. Holger Schüttrumpf

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Abstract

Water, the source of life and key element for economic and population growth, is the reason for many conflicts on earth. In light of climate change and global warming, it is even more important to use it carefully, as it will become even more scarce in countries already facing water scarcity.

Ethiopia is facing economic water scarcity as the theoretically water-rich country previously could not store large amounts of water from precipitation in the country's wet season in late summer due to lacking storage capacities. Since the construction of the Grand Ethiopian Renaissance Dam and three more dams planned along the Blue Nile, this has changed. As a developing country facing several droughts and famines in the previous years, solid food supply through extensive expansion of agriculture using the newly developed sources for water is assumed to be the key to success. As agriculture by far is the largest consumer of water compared to other industrial sectors, however, large potential for reduced discharges towards the downstream countries Sudan and Egypt emerge.

This dissertation examines how large the water abstraction from the Blue Nile river catchment area can be in the future based in a set of boundary conditions. Firstly, starting with the determination of potentially suitable areas for irrigated agriculture performing a Multi-Criteria Decision Analysis. Secondly, developing cropping patterns for the different agro-economical zones considering cash crops and food crops, and thirdly, determining the irrigation water demand for these pattern considered different irrigation methods.

The results show large variation depending on the criteria combined. A total of 94.640 km^2 or 47.47% of the Blue Nile Basin were determined as suitable for irrigated agriculture. The consideration of different irrigation techniques, methods, cropping pattern and climatic zones led to 48 scenarios for which the annual irrigation water demand being calculated. The values for annual water abstraction range from 29.25 to 689.28 BCM depending on the chosen scenario.

Kurzfassung

Wasser als Quelle des Lebens und Schlüsselelement für Wirtschafts- und Bevölkerungswachstum ist der Grund für viele Konflikte auf der Erde. Angesichts des Klimawandels und der globalen Erwärmung ist es umso wichtiger, sorgsam damit umzugehen, da es in Ländern, die bereits mit Wasserknappheit zu kämpfen haben, noch knapper werden wird.

Äthiopien ist mit wirtschaftlicher Wasserknappheit konfrontiert, da das theoretisch wasserreiche Land bisher nicht die Möglichkeit hatte, große Mengen Wasser aus Niederschlägen in der Regenzeit im Spätsommer zu speichern, da Speicherkapazitäten fehlten. Seit dem Bau des Grand Ethiopian Renaissance Dam und drei weiterer geplanter Staudämme entlang des Blauen Nils hat sich dies geändert. Als Entwicklungsland, das in den vergangenen Jahren mit mehreren Dürren und Hungersnöten konfrontiert war, gilt eine solide Nahrungsmittelversorgung durch eine extensive Ausweitung der Landwirtschaft unter Nutzung der neu erschlossenen Wasserquellen als Schlüssel zum Erfolg. Da die Landwirtschaft im Vergleich zu anderen Industriezweigen der mit Abstand größte Wasserverbraucher ist, ergeben sich für die Länder Sudan und Ägypten große Potenziale zur Verringerung der Abflüsse in den Unterlauf.

In dieser Dissertation wird auf der Grundlage der getroffenen Annahmen untersucht, wie groß die Wasserentnahme aus dem Einzugsgebiet des Blauen Nils in Zukunft sein kann, beginnend mit der Bestimmung potenziell geeigneter Flächen für die Bewässerungslandwirtschaft durch eine Multi-Kriterien Entscheidungsanalyse, der Entwicklung von Pflanzmustern für die verschiedenen agroökonomischen Zonen unter Berücksichtigung von Cash Crops und Food Crops und der Bestimmung des Bewässerungswasserbedarfs für diese Muster unter Berücksichtigung verschiedener Bewässerungsmethoden.

Die Ergebnisse zeigen große Unterschiede in Abhängigkeit von den kombinierten Kriterien. Insgesamt wurden 94.640 km^2 oder 47,47% des Einzugsgebietes des Blauen Nils als für die Bewässerungslandwirtschaft geeignet eingestuft. Die Berücksichtigung verschiedener Bewässerungstechniken, -methoden, Anbaumuster und Klimazonen führte zu 48 Szenarien, für die der jährliche Bewässerungswasserbedarf berechnet wurde. Die Werte für die jährliche Wasserentnahme reichen je nach gewähltem Szenario von 29,25 bis 689,28 BCM.

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List of Abbreviations

AHP ... *Analytical Hierarchy Process*
ALES ... *Automated Land Evaluation Systems*
ALSE ... *Agriculture Land Suitability Evaluator*
ANP ... *Analytical Network Process*
ANRS BoFED ... *Amhara National Region State Bureau of Finance and Economic Development*
ARAS ... *Additive Ratio Assessment*
AS ... *Appraisal Score*
AV ... *Average Solution*
BAA ... *Border Approximation Area*
BCM ... *Billion Cubic Meters*
CEC ... *Cation Exchange Capacity*
CI ... *Consistency Index*
CO ... *Characteristic Objects*
CoCoSo ... *Combined Compromise Solution*
CODAS ... *Combinative Distance-based Assessment*
COMET ... *Characteristic Objects Method*
COPRAS ... *Complex Proportional Assessment*
CR ... *Consistency Ratio*
CRILOS ... *Criterion Impacts LOS*
CRITIC ... *Criteria Importance Through Intercriteria Correlation*
CSA ... *Central Statistics Agency*
DEM ... *Digital Elevation Model*
DMM ... *Decision Making Matrix*
DSS ... *Decision Support System*
EDAS ... *Evaluation Based on Distance from Average Solution*
ELECTRE ... *Elimination Et Choix Traduisant la REalite*
ERVD ... *Election Based on relative Value Distance*
FAO ... *Food and Agriculture Organization of the United Nations*
GDP ... *Gross Domestic Product*
GERD ... *Grand Ethiopian Renaissance Dam*
GIS ... *Geographic Information System*
HRU ... *Hydrologic Response Unit*
IDOCRIW ... *Integrated Determination of Objective Criteria Weights*
IMPEND ... *Investment Model for Planning Ethiopian Nile Development*
ISLE ... *Intelligent System for Land Evaluation*
IWD ... *Irrigation Water Demand*
LC ... *Land Characteristics*
LECS ... *Land Evaluation Computer System*
LEIGIS ... *Land Evaluation Using an Intelligents Geographical Information System*
LMCS ... *Copernicus Land Monitoring Service*
LMU ... *Land Mapping Unit*
LQ ... *Land Qualities*
LSE ... *Land Suitability Evaluator*
LUT ... *Land Utilization Type*
MABAC ... *Multi-Attributive Border Approximation Area Comparison*
MAIRCA ... *Multi-Attributive Ideal Real Comparative Analysis*
MARCOS ... *Measurement Alternatives and Ranking according to Compromise Solution*
MCDA ... *Multi-Criteria Decision Analysis*

MCDE......Multi-Criterion Decision Evaluation
MEJ ...... Matrix of Expert Judgement
MEREC ......Methods based on the Removal Effects of Criteria
MicroLEIS ......Mediterranean Land Evaluation Information System
MoA......Ehtiopia Ministry of Agriculture
MOORA ...... Multi-Objective Optimization Method by Ratio Analysis
MOWIE...... Ministry of Water, Irrigation and Electricity
MSSI ......Modern Small-Scale Irrigation
NDA......Negative Distance from the average solution
NDVI ......Normalized Difference Vegetation Index
NIS ...... Negative Ideal Solution
OCRA......Operational Competitiveness Rating
PDA ......Positive Distance from the average solution
PIS...... Positive Ideal Solution
PROBID...... Preference Ranking On the Basis of Ideal average Distance
PROMETHEE ......Preference Ranking Organization Methods for Enrichments of Evaluations
RAM ...... Root Assessment Method
RI......Random Index
RIM......Reference Ideal Method
SJ ......Summed Judgement
SPOTIS ......Stable Preference Ordering Towards Ideal Solution
STD ......Standard Deviation weights
SWARA......Step-wise Weight Assessment Ratio Analysis
SWAT...... Soil and Water Assessment Tool
TDS ......Total Dissolved Solids
TOPSIS ...... Techniques for the Order of Prioritisation by Similarity to Ideal Solution
VEGES...... Vegetable Expert System
VIKOR......ViseKriterijumska Optimizacija I Kompromisno Resenje
WASPAS ...... Weighted Aggregated Sum Product Assessment
WD...... Water Demand
WPM ...... Weighted Product Model, Weighted Product Model
WRM ......Water Resources Modelling
WSM......Weighted Sum Model, Weighted Sum Model

1 Introduction

The global climate change and coping with its impacts on society, ecology, and economy already is and will perpetually be one of the main challenges of the 21st century. These effects of climate change appear in the shape of intensified weather conditions like longer droughts, higher peak temperatures, and fewer but therefore heavier rainfalls (FAO 2022).

Furthermore, progressing industrialization and the accompanying increase of health, wealth, and food security in the countries of the 2nd and 3rd world leads to increasing populations in these countries. (Bhaskara Rao 1997) Combining these developments of increasing populations on the one hand and fewer freshwater resources on the other hand, new ways to secure food supply with a focus on water withdrawal from the freshwater resources are necessary.

In the following sections, the main motivation behind this dissertation is discussed. Afterwards, the key research questions and methodologies used to answer these questions are presented. Finally, the overall structure of this thesis is outlined.

1.1 Motivation

While simply expanding the agricultural areas might appear to be the first choice to solve the problem, it might cause another one in areas with (transboundary) dependencies on the source of water. To avoid conflict arising from water abstractions, careful estimates are required. Still, it is important not to close eyes in front of an approaching worst-case scenario even if it might never become reality, and even if not in the near future, so that the parties being negatively affected can prepare their selves. Especially for Egypt and Sudan, the construction of the dam cascade along the Blue Nile is a thread to water security, and since both countries highly rely on the use of the Nile water for irrigated agriculture, also to food security. Despite reasonable complaints on imbalances in water distribution originating from colonial influences in the 20th century, it needs to be observed how much of the Nile's discharge might be constantly consumed in Ethiopia for potential irrigated agriculture in the future.

1.2 Objectives

The objective of this dissertation is to develop a comprehensive approach to calculate the water demand for agricultural projects based on areas, generally suited for agricultural usage. For doing so, a case study was carried out focusing on the Blue Nile River catchment area in Ethiopia as proof of concept due to its Grand Ethiopian Renaissance Dam (GERD) built between 2011 and 2022 and the cascade of three additional dams to be constructed along the Blue Nile. The developed approach is universally applicable for every environment on earth and the necessary data can be obtained from publicly available sources. Additionally, a set of scenarios will be developed including combinations of different irrigation approaches, irrigation techniques, cropping patterns, and climatic zones. These will be used to calculate water abstractions from the catchment area of the Blue Nile River. This will give an anticipation of non-available water resources in the area if a certain scenario becomes true.

Infront of this background the following, the main scientific questions arise:

Which are the necessary datasets needed to evaluate certain areas for their agricultural suitability?

The availability of comprehensive and complete datasets can be seen as the major obstacle when working with remote study areas. In most cases, a trade-off between the accuracy of the results and the availability of data must be made. This begins with inaccurate data, e.g. large cell sizes, and ends with complete lack of data availability. In this thesis, the available data will be reviewed and a set of crucial datasets will be determined, which are necessary on all accounts to assess agricultural suitability.

How can a certain area be evaluated regarding its agricultural suitability?

As various as the potential datasets are, so are the methods and ways to combine them to determine whether a certain area is suitable for agriculture or not, and if so to what extent an area is suitable. These methods can range from simple exclusion of areas based on several factors to complex multi-staged multi-criteria analysis. In this thesis, some of these methods will be evaluated out for their accuracy and their outputs will be compared.

How large will the water abstraction from the Blue Nile River system be based on the developed scenarios?

The answer to this question will be the focal point of the present thesis. Based on both traditionally planted crops, as well as under the given circumstances cultivatable crops – normally with higher economic value but therefore higher requirements – scenarios will be developed under consideration of irrigation types, methods and climate zones to be able to cover different choices farmers would have to make when setting up an agricultural scheme. Lastly, the different scenarios will be combined with the calculated values suitable for agriculture to receive crisp values for the water abstraction.

1.3 Outline

This thesis is made up of seven chapters.

Chapter 2 provides background information on the topic. First, the term decision analysis is defined and a collection of decision analysis methods and methods to obtain weights for the criteria are described. Afterwards, notably approaches to determine land suitability are elaborated. Lastly, the fundamentals of water resources management in Agriculture are explained as in cropping patterns, irrigation methods, and techniques.

Chapter 3 gives a brief introduction into the relevant characteristics and properties of the study area in the shape of an overall introduction, physical and climatic characteristics, the socio-economic and political status, and existing agricultural projects.

Chapter 4 encompasses a literature review of related research in land suitability analysis and irrigation water demand determination in the Blue Nile River basin.

Chapter 5 presents the approaches carried out during the process of finding the final method performed to reach the final results of this thesis. The specific results of each approach are critically reflected and potentials for refinement and improvement are given.

Chapter 6 comprises a case study performed to test the found work flow starting with defining the study area, determining the share of agriculturally suitable land for rainfed and irrigated agriculture in different climate zones, developed cropping patterns for each zone and calculation the irrigation water demand for each zone which indicates the overall irrigation water demand for the study area.

Chapter 7 summarizes the key findings, challenges and potential for optimization of this research, outlines upcoming challenges in the research field and gives recommendations for future research.

2 Background

This chapter acts as a necessary knowledge base apart from the general scientific knowledge in the research field. Since Decision Analysis, Land suitability and Water Resources Modelling are the main subjects of this thesis, these three dimensions are discussed in more detail.

The first section deals with the Decision Analysis, in particular the Multi-Criteria Decision Analysis (MCDA). Here, a collection of MCDA methods is presented. Since the outcome of MCDA is highly dependent on the weight, several approaches on how to obtain weights are presented as well. In the second section, the topic of land suitability is introduced and discussed, and different approaches are presented. Lastly, the different dimensions of water resources management, here irrigation methods, techniques, and cropping patterns are.

2.1 Decision Analysis

This section gives an insight into the subject of decision analysis in general. The necessity and general idea of MCDA is elaborated and different techniques are explained and compared to each other. Additional dimensions included in the MCDA are the process of assigning weights to the criteria to be combined and normalizing such criteria. This section also gives an overview of the existing weighting and normalization methods.

2.1.1 MCDA Methods

As many different application fields for MCDA exist, there also are many different ways to combine a predefined set of factors of different importance for the specific purpose of the result to achieve. In general, MCDA methods can be grouped depending on the type of information they are based on. (Larichev 2000). According to Larichev, 2000, there are MCDA methods based on quantitative measurements, qualitative initial measurements, pairwise comparison of alternatives and on qualitative measurements not converted to quantitative variables. Table 4 shows a selection of MCDA methods which are in the following briefly described in alphabetical order. It is emphasized, that the section below does not reflect a complete collection of methods due to the lack of relevance for the present work.

Analytic Hierarchy Process (AHP)

The AHP is one of the most applied methods in decision making. The assumption for this method is that the experience of the decision maker and the quality of the used data are on the same level of importance. Due to this principle, AHP is always subjective depending on the decision maker's decisions. The AHP in general can be divided into two phases: The phase of the hierarchic design and the phase of the evaluation. To minimize the effect of subjectivity, the hierarchy design can be achieved by combining several experts' opinions on the problem. The term 'hierarchy' for this method originates from the evaluation approach, as described later in this section. The design of the hierarchy previously achieved is performed in three steps. First, the levels and the concepts of the hierarchy need to be determined, then the concepts need to be defined, and lastly, the specific questions need to be formulated. Here the answers to the selected questions must be known, so that suitable criteria and weights are used in this process. If this is not the case, either the respective question is not meaningful or it is not comparable. In the second phase, the evaluation is done by a pairwise comparison of two alternatives resulting in a paired comparison matrix. Table 1 shows an example of a pairwise comparison matrix as in (Baniya 2008).

Table 1: Example of a Pairwise Comparison Matrix after (Baniya 2008)

Parameter	A	B	C	D	E	F	Weights	Ranking
A	1	2	7	3	5	3	0.365	1
B	1/2	1	6	3	5	2	0.264	2
C	1/7	1/6	1	1/2	1/4	1/2	0.064	6
D	1/3	1/3	4	1	4	1	0.127	3
E	1/5	1/5	2	¼	1	1/3	0.073	5
F	1/3	½	4	1	3	1	0.125	4
λ_{max} =6.428	CI = 0.086			CR = 0.069			Σ = 1	

As the name indicates, each factor is compared with another and a certain "intensity of importance" is selected. Vice versa, the corresponding reciprocal values are entered in the cells in which the two compared criteria switch places. The range of possible intensities is listed in Table 2.

Table 2: The Fundamental Scale used for Pairwise comparison (Saaty 2001)

Intensity of Importance	Qualitative Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of on over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored in its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

Having the comparisons done and the respective intensities indicated, the values necessary for the weighting can be calculated. Starting with the Eigenvector derived by the maximal Eigenvalue (λ_{max}) contained in the matrix, the Eigenvectors are determined for every criterion. Afterwards, the sum of the components of the Eigenvector is normalized (Chen et al. 2010). This results in the weights indicated in the eighth column, which can be ranked as observable in the column to the right of it. The consistency ratio (CR) is a value used to check if the variation in the results is acceptable. For good results, CR should be smaller than 0.1. If CR is larger than that, the intensities should be reviewed. (Baniya 2008) The CR is determined by dividing the consistency index (CI) by the random index (RI), which is dependent on the number of pairs in the pairwise matrix. (Baniya 2008) The CI for its part is calculated as follows:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{1}$$

While n is the number of criteria in the pairwise comparison matrix.

Analytic Network Process (ANP)

The ANP can be considered as a derivative of the AHP. While AHP, generates a hierarchic ranking, ANP provides results considering interdependencies between several criteria. The method is performed in four steps. First, the model needs to be constructed and the problem to be solved needs to be structured to gain better understanding of the problem. In this step, several clusters of combined criteria are built. Secondly, the pairwise comparison matrices and priority vectors have to be developed, which is done similar to the process for the AHP method. Due to that, the same comparison scale as described in the AHP section can be applied to indicate the relative importance of a criterion to another. For inverse comparison, the reciprocal values are used as well. In step three, a so-called "super-matrix" is formed. This is done by entering the local priority vectors from step two in the corresponding columns of the super matrix, which results in global priorities. If any elements show a zero in this matrix, the corresponding criteria does not affect the alternative chosen. Afterwards, the super matrix needs to be weighted by multiplying the matrix values in the cluster matrix. Then, the limit of the super matrix needs to be examined to obtain the relative influence of the matrix element to each other. This is done by raising the exponential powers of the former matrix. Having this done, the priorities of the elements are obtained through normalization of the matrix. The last and fourth step is the selection of the most favorable alternative. To do so, the super matrix from the previous step needs to be searched for the largest weight, which indicates the best alternative.

Additive Ratio Assessment (ARAS)

The Additive Radio Assessment is a relatively new introduced method from 2010. According to their developer Zavadskas and Turskis, ARAS is performed in three stages (Zavadskas and Turskis 2010). According to other authors who applied the method, the steps were additionally subdivided leading to a total of six steps. (Stanujkic et al. 2015) In the first stage, a decision-making matrix (DMM) is set up. The matrix consists of m of feasible alternatives in its rows and n reasonable criteria describing the alternatives in its columns. The performance value x_{ij} depends on the alternative i in terms of the j criterion. x_{oj} in this case represents the optimal value of the j criterion. The performance values x_{ij} and the weights w_j have to be set based on expert knowledge.

In the second stage, the criteria are being normalized so that criteria of different dimensions can be directly compared against each other. Normalization is done differently based on the preferred values x_{ij} should be maximal or minimal. For this matter, the preferred maximal x_{ij} value is divided by the sum of all m x_{ij} values, whilst for the preferred minimal x_{ij} values, the reciprocal value of x_{ij} is being divided by the sum of all m x_{ij} values. This process is displayed in the following equations (2) for maximal and (3) for minimal values.

$$x_{0j} = \max_i x_{ij}, if \max_i x_{ij} \text{ is the option of choice}; \quad (2)$$

$$x_{0j} = \min_i x_{ij}, if \min_i x_{ij} \text{ is the option of choice}. \quad (3)$$

In the third and last stage, the normalized values are now weighted according to their importance to the final result. This is done by assigning values between 0 and 1 to the respective criteria based on expert knowledge. The sum of all weights needs to be 1. These are then used to calculate the normalized-weighted values by multiplying the weights and the normalized criteria. Lastly, the optimality function S_i of each alternative is built by summing up all normalized weighted values for this respective alternative. The maximal value of S_i is the best, the minimal the worst one.

Combined Compromise Solution (CoCoSo)

This approach was developed by Morteza Yadzani in 2017 (Yazdani et al. 2019). CoCoSo aims to find a compromise solution between the objectives of different focuses. These can be for example ethical, technical, or financial objectives. It uses an integrated simple additive weighting and exponentially weighted product model as basis. The CoCoSo approach is done within five steps: First, an initial DMM is formed (see 4).

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} ; \quad i = 1,2, \dots, m; \; j = 1,2, \dots, n. \quad (4)$$

The matrix consists of m of feasible alternatives in its rows and n reasonable criteria describing the alternatives in its columns. The performance value x_{ij} depends on the alternative *i* in terms of the *j* criterion. In the second step, the criteria are being normalized applying the compromise normalization equation (5) after (Zeleny 1976) resulting in the normalization factor r_{ij} for each criterion.

$$r_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (5)$$

Subsequently, in step three, the total of the weighted comparability sequence and the power weight of comparability sequences for each alternative sum of the weighted comparability sequence S_i and the amount of the power weight of comparability sequences for each alternative Pi are calculated (6 & 7).

$$S_i = \sum_{j=1}^{n} (w_j r_{ij}) \tag{6}$$

$$P_i = \sum_{j=1}^{n} (r_{ij})^{w_j} \tag{7}$$

S_i is calculated using the grey relational general approach, while for P_i, the WASPAS multiplicative attitude is followed. In step four, there are three possible alternatives for the appraisal score *k* has to be calculate tough the arithmetic means of the sums of the weighted sum method (WSM) and the weighted product method (WPM) values (8), the sum of WSM and WPM's relative scores in compensation to the optimum (9) or the balanced compromise of the WSM and WPM scores (10). λ marks the Lagrange multiplicator necessary for optimization problems which occur when following this approach.

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m}(P_i + S_i)} \tag{8}$$

$$k_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \tag{9}$$

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)(P_i)}{(\lambda \max_i S_i + (1-\lambda)\max_i P_i)}\ ; 0 \leq \lambda \leq 1 \tag{10}$$

Lastly, in the fifth step, all the alternatives are ranked based on the combined k_i values previously determined in step 4. (11)

$$k_i = (k_{ia} k_{ib} k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \tag{11}$$

The higher the resulting *k* values, the more significant the respective alternative and the more favorable it is for selection.

Combinative Distance-based Assessment (CODAS)

The CODAS method makes use of the Euclidean distance in a first phase and the Taxicab distance in a second to rank the considered alternatives during a selection process. The reason for the two-phase approach is due to the possibility that two alternatives might not be comparable while only using the Euclidean distance methods. In this case, the Taxicab method is additionally used. Due to the nature of the two methods, -norm indifferent space for the criteria is required. The CODAS methods can be divided in 8 steps. Just as for the previously described CoCoSo method, a *n* x *m* decision making matric is developed in the first step (4). A linear normalization is done in step two. The resulting normalized performance values are weighted in step three to generate the weighted normalized decision matrix. New compared to previous approaches, the negative-ideal solution now has to be calculated according to formula 12 in the fourth step:

$$ns = [ns_j]_{1 \times m}\ ;\ ns_j = \ min_i r_{ij} \tag{12}$$

Afterwards, in step five both the Euclidean distance (13) and the Taxicab distance (14) are calculated.

$$E_i = \sqrt{\sum_{j=1}^{m} (r_{ij} - ns_j)^2} \tag{13}$$

$$T_i = \sum_{j=1}^{m} \left| r_{ij} - ns_j \right| \tag{14}$$

In step six, the relative assessment matrix R_a is constructed by determining the single values h_{ik} for each alternative. h_{ik} is calculated as displayed in equation 15.

$$h_{ik} = (E_i - E_k) + \left(\psi(E_i - E_k)\ \times (T_i - T_k)\right); k = 1, 2, \dots, n. \tag{15}$$

ψ is a threshold function to recognize the equality of the Euclidean distance

$$\psi(x) = \begin{cases} 1\ if\ |x|\ \geq \tau \\ 0\ if\ |x|\ < \tau \end{cases} \tag{16}$$

Here, τ is the threshold parameter based on subjective decision which is normally between 0.01 and 0.05. If τ is larger than the Euclidean distances of two alternatives, the Taxicab distance has to be considered for further perception. The last calculation is done in step seven. Here, the assessment score is calculated by

$$H_i = \sum_{k=1}^{n} h_{ik} \tag{17}$$

Finally, in the eighth step, the H_i values of all alternatives are ranked. The highest value marks the most preferred alternative for further selection.

Characteristic Objects Method (COMET)

In the COMET method, the fuzzy sets theory is used. This means that rather than numerical values, uncrisp ranges of values or terms are used. Compared to other methods, COMET does not have the disadvantage of the rank reversal phenomenon and the advantage to deal with imprecise data obtained from real-world observations. The rank reversal phenomenon as the terminus indicates causes a reversed order of the alternatives in the final result. The COMET method can be subdivided into five steps. In the first step, the dimensionality of the decision problem needs to be defined, which is done based on expert decisions. For a total of r criteria C, ($C_1, C_2, \dots, C_r$) a set of fuzzy numbers c_r are allocated to the respective criteria C_i. This results in the listing

$$\begin{aligned} C_1 &= \{C_{11}, C_{12}, \dots, C_{1c_1}\} \\ C_2 &= \{C_{21}, C_{22}, \dots, C_{2c_2}\} \\ &\dots \\ C_r &= \{C_{r1}, C_{r2}, \dots, C_{rc_r}\} \end{aligned} \tag{18}$$

In step two, the so-called characteristic objects (CO) are determined by creating the Cartesian product of the cores of the fuzzy numbers previously defined leading to an ordered set of *CO*s

$$CO = C(C_1) \times C(C_2) \dots \times C(C_r) \tag{19}$$

$$\begin{aligned} CO_1 &= C(C_{11}), C(C_{21}), \dots (C_{r1}) \\ CO_2 &= C(C_{11}), C(C_{21}), \dots (C_{r2}) \\ &\dots \\ CO_t &= C(C_{1c_1}), C(C_{2c_2}), \dots (C_{rc_r}) \end{aligned} \tag{20}$$

A check for arithmetic correctness can be done at this stage by calculating the value t which is equal to the count of the *CO*s and also equal to

$$t = \prod_{i=1}^{r} c_i \tag{21}$$

In step three, again based on expert knowledge, a "Matrix of Expert Judgement" (MEJ) is constructed by pairwise comparison of the *CO*s resulting in values α_{ij} for each pair.

$$MEJ = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1t} \\ \alpha_{21} & \alpha_{12} & \dots & \alpha_{2t} \\ \dots & \dots & \dots & \dots \\ \alpha_{t1} & \alpha_{t2} & \dots & \alpha_{tt} \end{pmatrix} \tag{22}$$

The values α_{ij} are assigned to the values 0.0, 0.5 or 1.0 depending on the expert's comparison ranking of CO_i and CO_j. If $CO_i < CO_j$, the 0.0 is assigned. If $CO_i = CO_j$, 0.5 is assigned and if $CO_i > CO_j$, 1.0 is assigned. Afterwards, a vertical vector is obtain using the following equation

$$SJ_i = \sum_{j=1}^{t} \alpha_{ij} \tag{23}$$

Whilst SJ_i describes the "Summed Judgement" of the alternatives *i*. After the preference values have been set, a vertical vector *P* is obtained. In the *i-th* row, the approximate values of preference for each CO_i can be taken from. In step four, the characteristic objects CO_i and their values of preferences Pi have to be converted into a fuzzy rule according to the scheme below for all CO_i to get the complete fuzzy rule base.

$$IF\ C(C_{1i}) AND\ C(C_{2i}) AND \dots THEN\ P_i \tag{24}$$

The fifth and last step, the fuzzy rule base outputs sets of crisp numbers for each of the alternatives. The sets with the structure $A_i = \{a_{1i}, a_{2i}, \dots, a_{ri}\}$ directly correspond to the criteria $C_1, C_2, \dots, C_r$ from step one. Lastly, Mandani's fuzzy inference methods are applied to calculate the preference if the alternatives *i*. The highest value displays the alternative preferred for selection.

Complex Proportional Assessment (COPRAS)

The COPRAS method can as well be divided into five steps, which cover the determination of the significance, the priority order, and the utility degree of the alternatives. COPRAS works under the condition that a direct proportional dependence exists between the significance and utility degree of the alternatives and the values and weights of the criteria. In the first step, the weighted normalized decision-making matrix *D* with *m* criteria and *n* alternatives is constructed. Doing so, dimensionless weighted values are generated from the comparative indices and can now be compared to each other. The comparison is done by applying the following equation (25)

$$d_{ij} = \frac{x_{ij} \times q_i}{\sum_{j=1}^{n} x_{ij}}, i = \overline{1,m}; j = \overline{1,n}. \tag{25}$$

Whilst x_{ij} displays the values of the criterion *i* of the alternative *j*. q_i indicates the weight of *i*. q_i can be cross-evaluated with the equation 26, according to which qi is the same as the sum of the dimensionless weighted index values of each criterion x_i

$$qi = \sum_{j=1}^{n} d_{ij}, i = \overline{1,m}; j = \overline{1,n} \tag{26}$$

In the second step, the weighted normalized indices d_{ij} are summed up. For this procedure, there are two possible desired statuses. If the results should be maximal, S_{+j} is calculated, for minimal values, S_{-j} is calculated as

$$S_{+j} = \sum_{i=1}^{m} d_{+ij}\,;\ S_{-j} = \sum_{i=1}^{m} d_{-ij}\,, i = \overline{1,m}; j = \overline{1,n}. \tag{27}$$

For S_{-j} and S_{+j}, there also is a cross-evaluation possible as the respective sums of all S_{-j} and S_{+j} values are always equal to the sums of the weights of the minimizing and maximizing criteria, respectively (28).

$$S_{+} = \sum_{j=1}^{n} S_{+j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{+ij}\,, S_{-} = \sum_{j=1}^{n} S_{-j} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{-ij}\,, i = \overline{1,m}; j = \overline{1,n} \tag{28}$$

Step three includes the calculation of the significance of the comparative alternative based on the description of positive and negative characteristics of the project, the MCDA is applied on. The relative significance can be calculated with equation (29).

$$Q_j = S_{+j} + \frac{S_{-min} \times \sum_{j=1}^{n} S_{-j}}{S_{-j} \times \sum_{j=1}^{n} \frac{S_{-min}}{S_{-j}}} \tag{29}$$

In step four, the priority of the project is determined by arranging the values Q_j while Q_1 has the highest priority. Since Q_j also reflects the degree of satisfaction of demand and goals, Q_{max} is the desired value to be figured out. Additionally, the degree of the utility of the project is derived by comparing the project analyzed in one process with Q_{max} (30), which gives a good overview about the effectiveness of different combinations of criteria and alternatives.

$$N_j = \frac{Q_j}{Q_{max}} 100\% \tag{30}$$

Lastly, the values N_j are ranked again with N_{max} being the most suited project for further selection.

Elimination Et Choix Traduisant la REalite (ELECTRE)

The ELECTRE method belongs to the outranking methods in which the criteria considered for the process are directly compared to each other by including the decision makers' preferences and set importances. The method is performed in nine steps. Before step one, the developed initial DMM X is normalized to achieve the normalized matrix X'. Then, in the second step, X' is weighted with the previously set weights by the decision maker set weights and in the third step, the Concordance and Discordance sets need to be determined. This is done accordingly:

$$C_{kl} = \{j | v_{kj} > v_{lj}\} \tag{31}$$

$$D_{kl} = \{j | v_{kj} < v_{lj}\} = J - C_{kl} \tag{32}$$

This is done so that the criteria are separated into the two sets so that in case of all criteria being of the same type (benefit or cost) another differentiation for each pair of alternatives can be done. In the fourth step, the concordance matrix is formed by building the sum of the weights which are referring to the concordance set as suggested below:

$$c_{kl} = \sum_{J \in C_{kl}} w_j \tag{33}$$

Having these, the matrix can be constructed using the values of the matrix elements c_{kl}. Accordingly, after the concordance matrix, the discordance matrix is determined in step five. The matrix elements d_{kl} are calculated as follows and the matric is set up afterwards:

$$d_{kl} = \frac{\max_{j \in D_{kl}} |v_{kj} - v_{ij}|}{\max_{j \in J} |v_{kj} - v_{lj}|} \tag{34}$$

As the term indicates, the discordance matrix elements d_{kl} indicate unfavorable alternatives, meaning that if d_{kl} is high, the related alternative should not be chosen. In step six, the Concordance Index or Dominance Matrix is determined.

$$\bar{c} = \sum_{\substack{k=1 \\ k \neq l}}^{m} \sum_{\substack{l=1 \\ l \neq k}}^{m} \frac{c_{kl}}{m(m-1)} \tag{35}$$

For $\bar{c}$, there is a threshold values defined which indicates whether a certain alternative A_k has the chance of dominating A_l. According to the literature, the threshold usually is set to 0.7. Having these, the bloomlean matrix *F* needs to be developed according to the following conditions:

$$f_{kl} = \begin{cases} 1; if\ c_{kl} \geq \bar{c} \\ 0; if\ c_{kl} < \bar{c} \end{cases} \tag{36}$$

Alike, the discordance dominance matrix is determined with the matrix elements as shown in equation *X* for the seventh step

$$\bar{d} = \sum_{\substack{k=1 \\ k \neq l}}^{m} \sum_{\substack{l=1 \\ l \neq k}}^{m} \frac{d_{kl}}{m(m-1)} \tag{37}$$

For $\bar{d}$, there also is a threshold value introduced which is usually set to 0.3. Here, as well a bloomlean matrix *G* is set up under the following conditions:

$$g_{kl} = \begin{cases} 1; if\ d_{kl} \geq \bar{d} \\ 0; if\ d_{kl} < \bar{d} \end{cases} \tag{38}$$

The eighth step, the Aggregate Dominance Matrix *E* needs to be set up by building the product of the previously created matrices *F* and *G*. Due to the several conditions of the previous steps, the matrix elements of *E* only can have values which are 0 or unequal to *k* and *l*. The ninth and last step is the elimination of the less favorable alternative. This is done by observing the matrix *E* from step eight and checking if the matrix elements e_{kl} have the value 1. If so, it is most likely that the alternative A_k is the better choice than A_l. It still can be, however that this does not indicate that A_k is the best of all considered alternatives.

$$E_e = \begin{bmatrix} - & 1 & 0 & 1 \\ 0 & - & 0 & 0 \\ 0 & 1 & - & 1 \\ 0 & 1 & 0 & - \end{bmatrix} \tag{39}$$

As in an example, the Aggregate Dominance matrix E_e each of the lines represents one alternative. If there is a matrix element with the value 1, in a line, it means that the respective alternative is performing less well. For example, for line 1, in column 2, the value is 1 which means that alternative A_2 is performing better as alternative A_1. Accordingly. For this example, the alternative A_2 is the best of all, as in its “own” line 2, it only has zeros as matrix element values so in direct pairwise comparison it outperforms all other alternatives.

Election Based on relative Value Distance (ERVD)

In the ERVD method is considered as a derivative of the TOPSIS method, which is described later in this chapter. The ERVD method, however, additionally requires the identification of reference points by the decision maker for each criterion. The utility function, which is applied in TOPSIS, is replaced by an adaptation of the value function based on prospect theory. This is to depict the dimension of the likelihood of the decision makers to take risks during the selection process, to maybe achieve higher profits. Additionally, this method has less problems than TOPSIS with the ranking reversal phenomenon already described in the section on the COMET method. To generate the ranking of the alternatives, the relative distance values to the positive (PIS) and negative ideals solutions (NIS) are determined. It is stated that at the terms describe PIS is the desired state to achieve and NIS is the state to avoid. Accordingly, the closer the outcome is to the PIS and the farther from NIS the better. This means that not the actual result is considered for the selection but only the distances to PIS (smaller) and NIS (larger). The process of the ERVD method is divided into seven steps. First, the reference points μ_j, = 1, …, n, have to be defined for each decision criterion C_1, …, C_n. j depicts the criteria which are compared to the reference point, μ_j. Afterwards, in step two the normalized DMM is generated. For comparison of the alternatives m for the criteria, they have to be normalized using a linear scale transformation.

$$r_{ij} = \frac{d_{ij}}{\sum_{i=1}^{m} d_{ij}} \tag{40}$$

If qualitative data is part of the input, it needs to be converted into crisp values first. Having calculated all possible values r_{ij}, the normalized DMM N can be formed which includes quantitative and qualitative information necessary for the selection process. In step three, alike the criteria, the reference points PIS and NIS have to be normalized using the following equation:

$$\varphi_j = \frac{\mu_j}{\sum_{i=1}^{m} d_{ij}} \tag{41}$$

In the fourth step, the value of the alternative A_i considering criterion C_j is determined, which is done by applying a modification of Tversky and Kahneman's value function. For this approach, there are two functions available: The increasing value function:

$$v_{ij} = \begin{cases} (r_{ij} - \varphi_j)^{\alpha} \ if \ r_{ij} > \varphi_j \\ -\lambda(\varphi_j - r_{ij})^{\alpha} \ otherwise \end{cases} \tag{42}$$

And the decreasing values function:

$$v_{ij} = \begin{cases} (\varphi_j - r_{ij})^{\alpha} \ if \ r_{ij} < \varphi_j \\ -\lambda(r_{ij} - \varphi_j)^{\alpha} \ otherwise \end{cases} \tag{43}$$

while λ stands for the attenuation factor of the losses, α stands for the diminishing sensitivity parameter. For α < 1, the results show a S-shape value function, for α > 1, an inverse S-shape function results from the calculation. The choice whether the increasing or the decreasing value function is used is based on whether the knowledge to be gained is directed to the maximal gain or the maximal loss resulting from the selected alternative. If the maximal gain should be figured out, the increasing values function is used. If the maximal loss should be figured out, the decreasing values function should be used. The difference between the calculated value and the reference point indicated the gain or loss, respectively. In step 5, the ideal positive A^+ for PIS and negative ideal solutions A^- for NIS are determined.

$$A^+ = \{v_1^+, \dots, v_n^+\}, A^- = \{v_1^-, \dots, v_n^-\}\ while\ v_j^+ = \underset{i}{max}\ v_{ij}\ and\ v_j^- = \underset{i}{min}\ v_{ij} \tag{45}$$

Having these, the individual separation measures have to be calculated for each alternative

$$S_i^+ = \sum_{j=1}^{n} w_j \cdot |v_{ij} - v_j^+|, for\ alternative\ i, i = 1, \dots, m \tag{46}$$

$$S_i^- = \sum_{j=1}^{n} w_j \cdot |v_{ij} - v_j^-|, for\ alternative\ i, i = 1, \dots, m \tag{47}$$

In the seventh step, the relative closeness of the alternative to the ideal solution is determined

$$\phi_i = \frac{S_i^-}{S_1^+ - S_i^-}, i = 1, \dots, m, while\ 0 < \phi < 1 \tag{48}$$

Desired outcome is to maximize ϕ since this means a smaller distance to the ideal positive and vice versa a larger distance to the negative ideal solution. There is, however a "shortcut" to simplify this process by performing the calculation done in steps five and six through a weighted sum model

$$\theta_i = \sum_{j=j}^{n} w_j - v_{ij.} \tag{49}$$

After calculating the performance values for all considered alternatives, the highest is the most preferred one for further selection.

Evaluation Based on Distance from Average Solution (EDAS)

In the EDAS method, the positive (PDA) and negative (NDA) distances from the average solution (AV) are used to figure out the most suited alternative during a selection process. Following this approach, otherwise commonly used reference values like the ideal or the nadir solution do not have to be determined. The targeted result is to outline alternatives with higher PDA and/or lower NDA, showing that these alternatives are better than the average solution. The process of the EDAS method can be divided into eight steps. In steps one and two, the criteria considered during the selection process to describe the possible alternatives are selected and the common decision-making matrix is formed. (See CoCoSo)

As for other DMM in other methods, X_{ij} marks the performance value of the alternative *i* and the criterion *j*. In step three, the average solution is calculated as follows:

$$AV = [AV_j]_{1\times m} \tag{50}$$

While at the same time

$$AV_j = \frac{\sum_{i=1}^{n} X_{ij}}{n} \tag{51}$$

During the fourth step, the PDA and the NDA are calculated according to the type of criteria

$$PDA = [PDA_{ij}]_{n\times m} \tag{52}$$

$$NDA = [NDA_{ij}]_{n\times m} \tag{53}$$

If the *j*th criterion is beneficial,

$$PDA_{ij} = \frac{\max\,(0, (X_{ij} - AV_j))}{AV_j} \tag{54}$$

$$NDA_{ij} = \frac{\max\,(0, \left(AV_j - X_{ij}\right))}{AV_j} \tag{55}$$

And if *j*th criterion is non-beneficial,

$$PDA_{ij} = \frac{\max\,(0, \left(AV_j - X_{ij}\right))}{AV_j} \tag{56}$$

$$NDA_{ij} = \frac{max(0, \left(AV_j - X_{ij}\right))}{AV_j} \tag{57}$$

In step five, the weighted sum of PDA and NDA from the *AV* are calculated for all possible alternatives *i* with w_j being the specific weight of any alternative.

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij} \tag{58}$$

$$SN_i = \sum_{j=1}^{m} w_j NDA_{ij}, \tag{59}$$

Step six is the normalization of the values *SP* and *SN* from step five

$$NSP_i = \frac{SP_i}{max_i(SP_i)}. \tag{60}$$

$$NSN_i = \frac{SN_i}{max_i(SN_i)}. \quad (61)$$

Afterwards, the appraisal score (AS) is calculated within step seven.

$$AS_i = \frac{1}{2}(NSP_i + NSN_i), where\ 0 \le AS_i \le 1. \quad (62)$$

In the last step eight, the appraisal scores are ranked in a decreasing order while the highest value indicates the most favorable and the lowest the least alternative for further selection.

Multi-Attributive Border Approximation Area Comparison (MABAC)

The MABAC method generates the distances of the potential alternatives to the border approximation area and is performed in six steps. In the first step, the initial DMM *X* is formed with *m* alternatives and *n* criteria to generate the alternatives A_i = (x_{i1}, x_{i2}, ..., x_{in}) while x_{ij} is the value of the *i*th alternative according to criterion *j*. Afterwards, the matrix is normalized to matrix *N* depending on the type of criteria in step two. If the criterion is of benefit type, it is normalized as follows:

$$n_{ij} = \frac{x_{ij} - x_i^-}{x_i^+ - x_i^-} \quad (63)$$

And if it is of cost type, as follows:

$$n_{ij} = \frac{x_{ij} - x_i^+}{x_i^- - x_i^+} \quad (64)$$

Whereas x_i^+ = max(x1, x2, ..., x_m), x_i^- = min(x1, x2, ..., x_m) are the maximal and minimal values of x_{ij} from the alternative values in the initial DMM *X*. In the third step, the weighted matrix *V* is calculated by processing the normalized alternatives n_{ij} with the following equation:

$$v_{ij} = w_i \cdot (n_{ij} + 1) \quad (65)$$

For the fourth step, the border approximation area (BAA) matrix *G* has to be created by calculating the values g_i for each alternative:

$$g_i = (\prod_{j=1}^{m} v_{ij})^{\frac{1}{m}} \quad (66)$$

The distance matrix *Q* then is simply calculated by subtracting the BAA matrix *G* from the weighted matrix *V* in step five. The BAA in general (here *G*) can be divided into two parts: The lower and the upper approximation area (here G^- and G^+). It is stated that the best alternative A^+ always lies within the upper approximation area G^+ and the worst alternative

A^- vice versa in the lower approximation area. This connection can be directly seen in the values q_{ij}:

$$A_i = \in \begin{cases} G^+ & if\ q_{ij} > 0 \\ G & if\ q_{ij} = 0 \\ G^- & if\ q_{ij} < 0 \end{cases} \tag{67}$$

To make the optimal choice following the MABAC method, as many values of q_{ij} of an alternative A_i should be > 0 which means most of these are closer to A^+ than to A^-. In the sixth and last step, the ranking values are calculated by summing the distance qi of the alternatives from the border BAAs:

$$S_i = \sum_{j=1}^{n} q_{ij}, j = 1, 2, \dots, n, i = 1, ., \dots, m. \tag{68}$$

The highest value S_{max} reflects the most preferred alternative for further selection.

Multi-Attributive Ideal-Real Comparative Analysis (MAIRCA)

The MAIRCA method differs from other comparable methods like TOPSIS or ELECTRE specifically in the linear normalization of the criteria, which is applied in this method. It suggests that the possible alternative can be ranked based on the difference between the ideal and the empirical weights and that the sum of differences between each criterion results in the total difference between each alternative. The alternative with the smallest calculated difference is the most preferred one for further selection. The MAIRCA method is performed within six steps. Step one is the formation of the initial DMM as commonly done in most of the methods available (69). In step two, the preference P_{ai} is selected as follows:

$$P_{A_i} = \frac{1}{m}; \sum_{i=1}^{m} P_{A_i} = 1, i = 1, 2, \dots, m \tag{69}$$

This is done due to the assumption made for this method, that the decision maker does not have any personal preference and is neutral to any kind of risk of the different alternatives, which might lead to a higher benefit. Accordingly, there is no difference to the decision maker between the Preferences P_{A1}, P_{A2}, …, P_{Am}. The third step is to set up the matrix T_p containing the theoretical evaluation elements. This is done by forming the product of P_{Am} and the specific criteria weights w_i.

$$t_{pij} = P_{A_m} \cdot w_i \tag{70}$$

The resulting matrix elements t_{pij} are then summarized in T_p:

$$T_p = \begin{bmatrix} t_{p11} & t_{p12} & \cdots & t_{p1n} \\ t_{p21} & t_{p22} & \cdots & t_{p1n} \\ \cdots & \cdots & \cdots & \cdots \\ t_{pm1} & t_{pm2} & \cdots & t_{pmn} \end{bmatrix} \tag{71}$$

By multiplying the theoretical evaluation matrix T_p with the initial DMM X created in step one, the real evaluation matrix T_r is calculated in step four.

$$T_r = \begin{bmatrix} t_{r11} & t_{r12} & \cdots & t_{r1n} \\ t_{r21} & t_{r22} & \cdots & t_{r1n} \\ \cdots & \cdots & \cdots & \cdots \\ t_{rm1} & t_{rm2} & \cdots & t_{rmn} \end{bmatrix} \tag{72}$$

The matrix element t_{rij} are calculated as follows

$$t_{rij} = t_{pij} = \left(\frac{x_{ij} - x_i^-}{x_i^+ - x_i^-} \right) \tag{73}$$

For the criteria that are of benefit type, so if they should be as high as possible, or

$$t_{rij} = t_{pij} = \left(\frac{x_{ij} - x_i^+}{x_i^- - x_i^+} \right) \tag{74}$$

for the criteria that are of cost type so if they should be as low as possible. Whereas x_i^+ = max(x1, x2, ..., x_m), x_i^- = min(x1, x2, ..., x_m) are the maximal and minimal values of x_{ij} from the alternative values in the initial DMM X. Subsequently in step five, the total gap matrix G is generated by subtracting the real evaluation matric T_r from the theoretical evaluation matrix T_p

$$G = T_p - T_r \tag{75}$$

The gap matrix elements g_{ij} are within the following interval depending on the relationship of the matrix elements from the theoretical and the real evaluation matrices:

$$gij = \begin{cases} 0, & if\ t_{pij} = t_{rij} \\ t_{pij} - t_{rij}, & if\ t_{pij} > t_{rij} \end{cases} \tag{76}$$

Since the preferred alternative is the one with the smallest difference to the theoretical evaluation, g_{ij} should go towards zero. Lastly, in the sixth step, the criteria functions (= ranking values) Q_i are calculated by forming the sum of the column of the total gap matrix G:

$$Qi = \sum_{i=1}^{n} g_{ij}\, , i = 1, 2, \ldots, m. \tag{77}$$

The smallest result is the preferred one for the further selection.

Measurement Alternatives and Ranking according to Compromise Solution (MARCOS)

The MARCOS method differs from other MCDA approaches as it already includes the PIS and NIS during the formation of the initial DMM. It defines the relationships between the different alternatives and the reference values (PIS and NIS). Afterwards, the utility functions are formed and their outcomes regarding the compromise between PIS and NIS are ranked. The method has seven steps to follow. Step one is the creation of an initial DMM with n criteria and m alternatives. In the second step, an "extended" initial matrix X is formed by defining the PIS and NIS solutions.

$$X = \begin{bmatrix} x_{NIS1} & x_{NIS2} & \cdots & x_{NISn} \\ x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \\ x_{PIS1} & x_{PIS2} & \cdots & x_{PISn} \end{bmatrix} \tag{78}$$

While $PIS = {}^{max}_{i}\, x_{ij}$, if the criterion is of benefit type and ${}^{min}_{i}\, x_{ij}$, if it is of cost type and

NIS = ${}^{min}_{i}\, x_{ij}$, if the criterion is of benefit type and ${}^{max}_{i}\, x_{ij}$, if it is of cost type.

In step three, the matrix elements of the extended initial matrix X are normalized

$$n_{ij} = \frac{x_{PIS}}{x_{ij}}, if\ the\ criterion\ is\ of\ cost\ type \tag{79}$$

$$n_{ij} = \frac{x_{ij}}{x_{PIS}}, if\ the\ criterion\ is\ of\ benefit\ type \tag{80}$$

The weights are being introduced in step four to calculated the matrix elements v_{ij} for the weighted matrix X

$$v_{ij} = n_{ij} \cdot w_j \tag{81}$$

The fifth step it to determine the utility degrees of the alternatives A_i depending on the relation to PIS and NIS:

$$A_i^+ = \frac{S_i}{S_{PIS}} \tag{82}$$

$$A_i^- = \frac{S_i}{S_{NIS}} \tag{83}$$

For this step, the knowledge on the sum on the matrix elements S_i of the weighted matrix V is necessary.

$$S_i = \sum_{i=1}^{n} v_{ij} \tag{84}$$

In step six, the utility function of the alternatives $f(A_i)$ is set up which can be considered as the compromise between the alternatives and PIS and NIS, respectively. First, the utility $f(A^+)$ and $f(A^-)$ relating to PIS and NIS need to be calculated:

$$f(A_i^+) = \frac{A_i^-}{A_i^+ + A_i^-} \tag{85}$$

$$f(A_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \tag{86}$$

Then, $f(A_i)$ can be calculated as follows:

$$f(A_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \tag{87}$$

In the last, seventh step, the outcomes of the utility functions for each alternative are ranked. The alternative with the highest outcome is the preferred one for the further selection.

Multi-Objective Optimization Method by Ratio Analysis (MOORA)

The MOORA method developed in 2004 starts with the construction of the initial DMM. Weights have to be assigned afterwards depending on the method chosen by the decision maker. The MOORA method itself, after DMM and weights have been determined, consists of four steps. In the first step, the initial DMM is normalized by applying the following equation for all matrix elements a_{ij}:

$$x_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{88}$$

Afterwards, in step two, the weights are being introduced to the normalized matrix to generate the weighted normalized matrix elements.

$$W_{ij} = w_j \cdot x_{ij} \tag{89}$$

In the third step, the priorities need to be calculated. The priorities are the differences between the sums of the benefit and non-benefit criteria.

$$Q_i = \sum_{j=1}^{n} W_{ij} \tag{90}$$

In the last step four, the values Q_i are ranked. The higher the value, the better, and the highest value Q_{max} is the most preferred alternative for further selection.

Operational Competitiveness Rating (OCRA)

The OCRA method uses the efficiency of the available competitive alternatives for the ranking process. It also refers to the relations of the alternative's beneficial and non-beneficial effect and combines them to obtain the final ranking. OCRA is performed in six steps. The method starts with the creation of the initial DMM *X* using the common variables *i* for the alternative, *j* for the criteria and *x* for the matrix elements. In step two, only the non-beneficial input criteria are determined as follows:

$$\bar{I}_i = \sum_{j=1}^{g} w_j \frac{\max(x_{ij}) - x_{ij}}{\min(x_{ij})} \tag{91}$$

For the third step, a linear preference rating to the non-beneficial criteria has to be calculated according to equation (92)

$$\bar{\bar{I}}_i = \bar{I}_i - \min(\bar{I}_i) \tag{92}$$

In step four and five, the beneficial input criteria and the preference ratings are calculated accordingly as for the non-beneficial input criteria:

$$\bar{O}_i = \sum_{j=g+1}^{n} w_j \frac{x_{ij} - \min(x_{ij})}{\min(x_{ij})} \tag{93}$$

$$\bar{\bar{O}}_i = \bar{O}_i - \min(\bar{O}_i) \tag{94}$$

In the last step six, the preference rating values are determined by adding the linear preference ratings of the beneficial and non-beneficial input criteria for the respective alternative observed and subtracting the sum of the minimal linear preference rating of both the beneficial and non-beneficial input criteria:

$$P_i = \left(\bar{\bar{I}}_i - \bar{\bar{O}}_i\right) - \min\left(\bar{\bar{I}}_i - \bar{\bar{O}}_i\right) \tag{95}$$

The values P_{imax} marks the alternative with the highest performance and hence should be considered for the further selection process.

Preference Ranking On the Basis of Ideal-average Distance (PROBID)

The PROBID method is based on the relation of predefined alternatives to the ideal and average solutions. There is a simplified version of PROBID available, called sPROBID which only takes the first and last quarters of the ideal solutions into account. The presented method is subdivided into six steps. First, the previously created DMM is normalized using the vector normalization method

$$F_{ij} = \frac{f_{ij}}{\sqrt{\sum_{k=1}^{m} f_{kj}^2}} \tag{96}$$

In the second step, the normalized DMM is weighted using the weights w_j.

$$v_{ij} = F_{ij} \cdot w_j \tag{97}$$

Step three is the calculation of the solutions from the PIS to the NIS. As mentioned under the section on the ERVD method, PIS is the best alternative considering all criteria. Accordingly, following the PROBID method, there is also a 2nd PIS which is the alternative with the second-best values for all criteria, a 3rd PIS which is the alternative with the third-best values for all criteria, and so on. The "last" PIS then is equal to the NIS. Having these, the average values of each column of the weights normalized matrix are calculated:

$$\bar{v}_j = \frac{\sum_{k=1}^{m} v_{(k)j}}{m} \tag{98}$$

In the fourth step, the Euclidean distance is determined (99) and afterwards the distance to the average solution needs to be calculated as follows:

$$S_{i(avg)} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{(k)j})^2} \tag{99}$$

In step five, the overall PIS is calculated (100) if the numbers of rows in the weighted normalized DMM is odd

$$S_{i(PIS)} = \left\{ \sum_{k=1}^{(m+1)/2} \frac{1}{k} S_{i(k)} \right. \tag{100}$$

or (101) if the numbers of rows in the weighted normalized DMM is even.

$$S_{i(PIS)} = \left\{ \sum_{k=1}^{m/2} \frac{1}{k} S_{i(k)} \right. \tag{101}$$

Accordingly, this step is done for the NIS if the numbers of rows in the weighted normalized DMM is odd:

$$S_{i(NIS)} = \left\{ \sum_{k=(m+1)/2}^{m} \frac{1}{m-k+1} S_{i(k)} \right. \tag{102}$$

Or if the numbers of rows in the weighted normalized DMM is even

$$S_{i(NIS)} = \left\{ \sum_{k=\frac{m}{2}+1}^{m} \frac{1}{m-k+1} S_{i(k)} \right. \tag{103}$$

For all $S_{i(PIS)}$ and $S_{i(NIS)}$ is applies that the weights of the respective PISs (PIS, 2nd PIS, 3rd PIS, …) increase with the number of the ideal solution. The sixth step is the determination of the ration between the PIS and NIS:

$$R_i = \frac{S_{i(PIS)}}{S_{i(NIS)}} \tag{104}$$

And subsequently the performance score of every alternative is determined as well:

$$P_i = \frac{1}{1 + R_i^2} + S_{i(avg)} \tag{105}$$

If R_i -> 0, then the alternative *i* is close to the PIS and accordingly farer away from the NIS. This also means that P_i is getting larger. The opposite effect happens, when the alternative *i* is closer to the NIS than to the PIS. For step six, there is an alternative approach when the sPROBID method is pursued. Here, only the top and bottom quarters of the ideal solutions are considered to determine the PIS and NIS. The equation resulting from this looks as follows:

$$S_{i(PIS)} = \begin{cases} \sum_{k=1}^{m/4} \frac{1}{k} S_{i(k)}, when\ m \geq 4 \\ S_{i(1)}, when\ 0 < m < 4 \end{cases} \tag{106}$$

The remaining calculations for R_i and P_i remain the same. Depending on the type of the criterion (cost or benefit type), small R_i or P_i values are desired and the minimal values indicate the alternative which is exposed as the most preferred to choose.

Preference Ranking Organization Methods for Enrichment of Evaluations I & II (PROMETHEE I & II)

For the PROMETHEE method, there are two versions I & II available. The difference between the two is that PROMETHEE I only considers a selected set of possible alternatives while PROMETHEE II considers all of them. Both are based on the multi-criteria net flow and include both indifferences and preferences. The last is called the “preorder”. This method is performed within four steps. Before step one, the initial DMM is formed, although in the literature considered for this review, the matrix is displayed as at “evaluation table” (Table 3).

Table 3: Evaluation table (Sałabun et al. 2020)

a	$g_1(.)$	$g_2(.)$	…	$g_n(.)$
	w_1	w_2	…	w_n
a_1	$g_1(a_1)$	$g_2(a_1)$	…	$g_n(a_1)$
a_1	$g_1(a_2)$	$g_2(a_2)$	…	$g_n(a_2)$
…	…	…	…	…
a_m	$g_1(a_m)$	$g_2(a_m)$	…	$g_n(a_m)$

After doing so, the values for the preference function need to be determined. This is done by setting up the function *F* of the difference of two evaluations, which equals the preference function *P*, which is calculated for each criterion and lies always between 0 and 1.

$$P(a,b) = F[d(a,b)] \tag{107}$$

While *d(a,b)* is generated from the pairwise comparison

$$d(a,b) = g(a) - g(b) \tag{108}$$

Using the preference function, the decision maker can make adjustments. This can be done by applying equation (109) and (110)

$$q = \overline{D} - k \cdot \sigma_D \tag{109}$$

$$p = \overline{D} + k \cdot \sigma_D \tag{110}$$

While *D* is a positive value out of the results of *d(a,b)* and *k* is a factor to customize the result. In the second step, the aggregated preference indices need to be calculated as follows:

$$\begin{cases} \pi(a,b) = \sum_{j=1}^{n} P_j(a,b)w_j \\ \pi(b,a) = \sum_{j=1}^{n} P_j(a,b)w_j \end{cases} \tag{111}$$

P_i indicates the preference of a over b considering all criteria. However, for being able to do so, the following set of properties must be true for the set of alternatives A:

$$\begin{cases} \pi(a,a) = 0 \\ 0 \le \pi(a,b) \le 1 \\ 0 \le \pi(b,a) \le 1 \\ 0 \le \pi(a,b) + \pi(b,a) \le 1 \end{cases} \tag{112}$$

In step three, the positive (113) and negative (114) outranking flows are calculated

$$\phi^{+}(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x,a) \tag{113}$$

$$\phi^{-}(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x,a) \tag{114}$$

The last step four the ranking is done by subtracting the negative outranking flow on an alternative from the positive one

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a) \tag{115}$$

The outcomes of this step are the ranking values of which the largest one stands for the alternative that is most preferred for further selection.

Root Assessment Method (RAM)

The Root Assessment Method uses a radical expression of the possible alternatives to solve the decision problem. In this method, no pairwise comparison or transformations are necessary and both beneficial and non-beneficial criteria can be included. It is performed in five steps. Before starting with the first step, the initial DMM X is set up as usual and the weights for each criterion are defined. Then in step one, the matrix X is normalized applying the linear sum normalization described in detail later. The normalized matrix can be labelled as X'. Then, in the second step, the weighted normalized DMM Y is determined by multiplying the matrix elements of the normalized DMM with the specific weights w_{ij}. Step three is the normalized scores of the beneficial (116) and non-beneficial criteria (117) are calculated as follows:

$$S_{+i} = \sum_{j=1}^{n} y_{+ij} \tag{116}$$

$$S_{-i} = \sum_{j=1}^{n} y_{.ij} \tag{117}$$

For the fourth step, the overall score of the respective alternatives as shown below

$$RI_i = \sqrt[2+S]{2 + S_{+i}} \tag{118}$$

The last step five is the ranking of the previously calculated values RI_i. The larger the value, the better the outcome of the referring alternative A_i is. Hence, the alternative with the highest RI_i should be chosen.

Reference Ideal Method (RIM)

The Reference Ideal Method, as its name indicates, makes use of ideal reference points chosen by the decision maker and the difference between the ideal reference points and the alternative observed. RIM claims to be independent from the type of data, and also that the rank reversal phenomenon does not occur in this method. RIM is performed within seven steps. The first step is the preparation of the actual method by defining necessary variables like the range of the possible outcomes t_j, the reference ideal s_j and the specific weights w_j. All these variables have to be set for each criterion j. s_j of course has to be located within the previously set range t_j. Afterwards, in the second step, the initial DMM X is created and then normalized to the normalized matrix Y with the reference ideal in step three. This normalization approach is further explained in the respective section on the normalization methods. The fourth step is the weighting of Y. The result is the weighted normalized matrix Y'. For step five, the positive and negative variations of the normalized reference ideal for each alternative A_i need to be calculated as follows:

$$I_i^+ = \sqrt{\sum_{j=1}^{n} (y'_{ij} - w_j)^2} \tag{119}$$

$$I_i^+ = \sqrt{\sum_{j=1}^{n} (y'_{ij})^2} \tag{120}$$

In step six, the relative indices for each of the Alternatives A_i are calculated

$$R_i = \frac{I_i^-}{I_i^+ + I_i^-} \tag{121}$$

Lastly, in the seventh step, the alternative A_i are ranked according to their relative indices while the highest marks the best option to choose.

Stable Preference Ordering Towards Ideal Solution (SPOTIS)

The SPOTIS method claims to have low complexity and also to not be affected by the rank reversal phenomenon. It is also a method. pursuing the comparison of the possible alternatives with the ideal solutions rather than the comparison between the alternatives. The method is carried out in five steps. First, the range of the possible outcomes has to be defined. In the second step, the PIS and NIS need to be defined. Then, the normalized distance considering the ideal solutions for all criteria is computed in step three. The fourth step is the calculation of the average distances. Lastly, in the fifth step, the resulting average distances are ranked in a descending order. The highest value belongs to the alternative which should be prioritized.

Techniques for the Order of Prioritisation by Similarity to Ideal Solution (TOPSIS)

TOPSIS also belongs to the methods that can process fuzzy datasets. In contrast to other methods, in which the preferred solution is determined based on the closeness to the optimal solution or positive ideal solution (PIS), in TOPSIS the largest distance to the worst solution or negative ideal solution (NIS) is used for this purpose. TOPSIS is performed in six steps. In the first step, the DMM A is formed while w_j represents the relative weight of the criterion C_j in alternative A_i. d_{ij} is the rating of the respective alternative A_i. The matrix is normalized to make the alternative rating comparable as follows:

$$r_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^{m} d_{ij}^2}}, i = 1, \dots, m; j = 1, \dots, n. \tag{122}$$

In step two, the values V_{ij} for the weighted normalizes DMM is calculated:

$$v_{ij} = w_j \cdot r_{ij}, i = 1, \dots, m; j = 1, \dots, n; where \sum_{j=1}^{n} w_j = 1. \tag{123}$$

The third step is to determine the positive ideal and negative solution are calculated according to the equation already given under the section on the ERVD method (45). The same applied for the separation measures in the fourth (46) and the fifth step (47).

Accordingly, the sixth step closes the method with the raking of closeness to the ideal solution. The higher the resulting values are, the better the respective alternatives, the values belong to are.

ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

This compromise ranking method "VIsekriterijumska optimizacija i KOmpromisno esenje" (VIKOR) means multi-criteria optimization and compromise solution in Serbian, determines the weight stability intervals, using the methodology presented in (Duckstein and Opricovic 1980). The goal of this method is to obtain the alternative that is the closest to the ideal solution. VIKOR is very similar to PROMETHEE, but differs in the basic interpretation of closeness to the ideal solution. The method is carried out in five steps. Before starting, it is considered as preliminary work to set up the initial DMM and perform a normalization on it. In the first step, the PIS and NIS need to be figured out, depending on the information of the overserved criteria, which are of cost type or of benefit type. Step two is the calculation of the ranking values S_i and R_i as follows:

$$S_i = \sum_{j=1}^{n} w_j \frac{\left(f_j^+ - f_{ij}\right)}{\left(f_j^+ - f_j^-\right)} \tag{124}$$

$$R_i = \max_j \left[w_j \frac{\left(f_j^+ - f_{ij}\right)}{\left(f_j^+ - f_j^-\right)} \right] \tag{125}$$

While $f_j^+ = \max_i f_{ij}, f_j^- = \min_i f_{ij}$ for profit and $f_j^+ = \min_i f_{ij}, f_j^- = \max_i f_{ij}$ for cost type criteria. Afterwards a third ranking values Q_i is calculating using the previous two ones introducing the variable v as an additional weighting factor:

$$Q_i = v \frac{(S_i - S^+)}{S^- - S^+} + (1 - v) \frac{(R_i - R^+)}{(R^- - R^+)} \tag{126}$$

While $S^+ = max_i S_i, S^- = min_i S_i$ and $R^+ = max_i R_i, S^- = min_i R_i$

The obtained ranking values should be ranked in an ascending order for the fourth step so that three different ranking lists are available. It is now the task of the decision maker to decide which of the ranking values are considered for the final decision of the alternative in step five or not.

Weighted Aggregated Sum Product Assessment (WASPAS)

WASPAS can be described as a combination of the WPM and WSM models. Considering the equation for these, the WASPAS equation results as follows:

$$Q_i = \lambda \sum_{j=1}^{n} \bar{x}_{ij} w_j + (1 - \lambda) \prod_{j=1}^{n} \left(\bar{x}_{ij}\right)^{w_j}, \lambda = 0, \dots, 1. \tag{127}$$

Weighted Product Model (WPM)

The Weighted Product Mode (WPM) together with the WSM is one of the basic MCDM methods and hence very often applied or included in other, more complex MCDM methods.

The model's outputs values Q for each alternative m of n decision criteria performance values x_{ij} and the relative significance w_j.

$$Q_i^{(1)} = \prod_{j=1}^{n} (\bar{x}_{ij})^{w_j} \tag{128}$$

Whilst the values for the criteria are normalized as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{max_i x_{ij}} \tag{129}$$

The resulting values Q_i result in a ranking of the alternatives of which the preferable one is selected.

Weighted Sum Model (WSM)

The Weighted Sum Model (WSM) together with the WPM is one of the basic MCDM methods and hence very often applied or included in other, more complex MCDM methods. The model outputs values Q for each alternative m of n decision criteria considering the performance values x_{ij} and the relative significance w_j.

$$Q_i^{(2)} = \sum_{j=1}^{n} \bar{x}_{ij} w_j \tag{130}$$

Whilst the values for the criteria are normalized as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{max_i x_{ij}} \tag{131}$$

The resulting values Q_i result in a ranking of the alternatives of which the preferable one is selected.

Table 4: MCDA methods included in the review

Method	Acronym	Source(s)
Analytic Hierarchy Process	AHP	(Saaty 2001; Baniya 2008)
Analytic Network Process	ANP	(Taherdoost and Madanchian 2023)
Additive Ratio Assessment	ARAS	(Zavadskas and Turskis 2010; Stanujkic et al. 2015)
Combined Compromise Solution	CoCoSo	(Yazdani et al. 2019)
Combinative Distance-based Assessment	CODAS	(Badi and Abdulshahed 2017)
Characteristic Objects Method	COMET	(Salabun et al. 2018)
Complex Proportional Assessment	COPRAS	(Zavadskas et al. 2008)
Election Based on relative Value Distance	ERVD	(Shyur et al. 2015)
Evaluation based on Distance from Average Solution	EDAS	(Keshavarz Ghorabaee et al. 2015)
Multi-Attributive Border Approximation area Comparison	MABAC	(Pamučar and Ćirović 2015)
Multi-Attribute Ideal-Real Comparative Analysis	MAIRCA	(Pamucar et al. 2018; Gigović et al. 2016; Aksoy 2021)
Measurement Alternatives and Ranking according to Compromise Solution	MARCOS	(Stević et al. 2020; Ulutaş et al. 2020)(Stević et al. 2020; Ulutaş et al. 2020)
Multi-Objective Optimization Method by Ratio Analysis	MOORA	(Pardalos and Brauers 2004; Hussain and Mandal 2016)
Operational Competitiveness Ratings	OCRA	(Parkan 1994; Işık and Adalı 2016)
Preference Ranking On the Basis of Ideal-average Distance	PROBID	(Wang et al. 2021)
Preference Ranking Organization Method for Enrichment of Evaluations I & II	PROMETHEE I & II	(Brans et al. 1986)
Root Assessment Method	RAM	(Sotoudeh-Anvari 2023)
Reference Ideal Method	RIM	(Cables et al. 2016)
Stable Preference Ordering Towards Ideal Solution	SPOTIS	(Dezert et al. 2020)
Techniques for the Order of Prioritisation by Similarity to Ideal Solution	TOPSIS	(Liu 2009; Li et al. 2011; Sałabun et al. 2020)
ViseKriterijumska Optimizacija I Kompromisno Resenje	VIKOR	(Duckstein and Opricovic 1980)
Weighted Aggregated Sum Product Assessment	WASPAS	(Zavadskas et al. 2012)
Weighted Product Model	WPM	(Fishburn et al. 1968)
Weighted Sum Model	WSM	(Fishburn et al. 1968)

2.1.2 Weighting Methods

During the MCDA process, several criteria/factor/variables need to be combined to find the best possible alternative to choose. Of course, not all criteria considered for a decision have the same importance, i.e. weight. For example, when a certain plot is considered for agricultural use, it is more important that the temperature lies in the range the crops to cultivate can tolerate than the content of certain nutrients in the soils like Nitrogen or Phosphorus because it can be substituted with fertilizers. Accordingly, the latter would have lower weights. In his section, a collection of the commonly applied weighting methods is presented and briefly described.

Angular/Angle weights

The Angular/angle weights method uses a geometrical approach to objectively determine the specific weights of criteria. It is assumed that in a decision matrix X with n attributes, the attribute n+1 in the last column does not affect the other n attributes. It is now set as a reference point with the weight zero. All the other attributes are now measured for their weight according to the angle u_j to the reference point as follows.

$$u_j = arccos\left(\frac{\sum_{i=1}^{m} b_{ij}}{\sqrt{\sum_{i=1}^{m}\left(b_{ij}\right)^2}}\right) \tag{132}$$

The specific weights afterwards as calculated as below.

$$w_j = \frac{u_j}{\sum_{j=1}^{n} u_j} \tag{133}$$

Generally, it can be stated that the larger u_j, the higher the weight of the respective attribute is.

Criterion Impacts LOS (CRILOS)

The CRILOS method is based on the relative impact loss of a certain criterion in case a different one is figured out to be the optimum. The method is performed in three steps. First, a transformation of the minimized criteria r_{ij} to be maximized ones has to be performed:

$$\bar{x}_{ij} = \frac{x_{ij}}{max_i x_{ij}} \tag{134}$$

In the second step, the maximal values of each column of the resulting matrix X are determined

$$x_j = max_i x_{ij} = x_{k_i j} \tag{135}$$

Where k_j is the number of the row of the maximal value. The maximal values are now used to construct the matrix A, were $a_{ii} = x_i$ and $a_{ij} = x_{kij}$. This means that in the principal diagonal of A, the maxima of all criteria are displayed. In the third step, the relative loss matrix P with the matrix elements p_{ij} is developed as follows:

$$p_{ij} = \frac{x_j - a_{ij}}{x_j} = \frac{a_{ii} - a_{ij}}{aii} \tag{136}$$

The idea is now that the matrix elements (i.e. weights for the DMM) p_{ij} indicate he relative loss of criterion j if criterion I is selected. Hence, if the loss is small, the weight w_i is getting larger.

Criteria Importance Through Intercriteria Correlation (CRITIC)

The CRITIC method makes use of the so-called contrast intensity and the conflicting character the of considered evaluation criteria. The method is performed in 3-4 steps depending on the definition and the use of "shortcuts". First, the generic variable x_{aj} is determined by building the index of the functions $f_m(a)$ of the decision problems.

$$x_{aj} = \frac{f_j(a) - f_{j^*}}{f_j^* - f_{j^*}} \tag{137}$$

while f^*_j is the performance which is closest to the optimum and f_j^* which is the closest to the pessimum. When observing the jth criterion of x, the vector x_j is generated which includes the scores of all possible alternatives. Calculating the standard deviation σ_a of this vector, the contrast intensity of the respective criterion is determined. In the second step, an m x m matrix is set up making use of the linear correlation coefficient r_{jk} between the vector x_j and x_k:

$$\sum_{k=1}^{m} (1 - r_{jk}) \tag{138}$$

As CRITIC combines the contrast intensity and the conflicting character, the two previous equations could also be combined in a "shortcut" as follows to generate values for the information emitted by the jth criterion C_j:

$$C_j = \sigma_j \cdot \sum_{k=1}^{m} (1 - r_{jk}) \tag{139}$$

The higher C_j, the more important is it for the process and accordingly the higher the weight is. Lastly, C_j should be normalized to enhance the objectivity:

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_k} \tag{140}$$

Entropy weights

The Entropy weights methods can be divided into X steps. For this method, the entropy E_j using the normalized *j*th criterion for the *i*th alternative needs to be calculated in the first step.

$$E_{j=} -\frac{1}{\ln n}\sum_{i=1}^{n}\tilde{r}_{ij}\cdot ln\tilde{r}_{ij}; 0 \leq E_j \leq 1 \tag{141}$$

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \tag{142}$$

Afterwards, in step two, the degree of variation on the criterion is calculated as follows:

$$d_j = 1 - E_j \tag{143}$$

Although for the determination of E_j, the normalized criteria values r_{ij} are use, E_j itself is no normalized leading to also not normalized d_j values. Accordingly, to obtain the final entropy weighs W_j, a simple normalization is performed:

$$W_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{144}$$

Equal/Means weights

The method of equal or means weights is one of the simplest methods to apply. The weights are obtained by dividing 1 by the number *n* of criteria considered:

$$w_j = \frac{1}{n}. \tag{145}$$

Integrated Determination of Objective Criteria Weights (IDOCRIW)

In the IDOCRIW method, a set of criteria with different significances is set up and their respective weights are combined to obtain an overall weight. Having this, the previously presented methods of the entropy weights and impact loss weights (CILOS) can be combined. The results are aggregate weights w_j.

$$\omega_j = \frac{q_j W_j}{\sum_{j=1}^{m} q_j W_j} \tag{146}$$

The resulting weights, however, will lower the significance of the criteria because the losses compared to the losses of the criteria are getting higher. On the other hand, the variation of the individual values of the criteria is being shown.

Methods based on the Removal Effects of Criteria (MEREC)

In the MEREC method, it is observed how the weights for certain criteria in a DMM change when specific other criteria are removed. Through this approach, the method differs from most of the other methods as most are based on the inclusion of criteria rather than the exclusion as it is the case for MEREC. The method is carried out in six steps. First, an initial DMM has to be set up, then in the second step the matrix is normalized and all matrix elements are transformed to the minimization type resulting in the matrix elements n^x_{ij}. The third step is the logarithmic calculation of the performance values S_i of the observed alternatives as follows:

$$S_i = ln\left(1 + \left(\frac{1}{m}\sum_j \left|ln\left(n_{ij}^x\right)\right|\right)\right) \tag{147}$$

In the fourth step, the performance values of the alternatives are again calculated, but now while removing each criterion.

$$S'_{ij} = ln\left(1 + \left(\frac{1}{m}\sum_{k,k\neq j} \left|ln\left(n_{ij}^x\right)\right|\right)\right) \tag{148}$$

Step five is the determination of the removal effect of the *j*th criterion. This is done by adding all the absolute deviations related to the results S_i from the third and S'_{ij} from the fourth step.

$$\varepsilon_j = \sum_i \left|S'_{ij} - S_i\right| \tag{149}$$

In the sixth step, the objective weights are derived from the removal effect ε_j through normalization:

$$w_j^o = \frac{\varepsilon_j}{\sum_k \varepsilon_k} \tag{150}$$

Standard Deviation weights (STD)

To generate the standard deviation weights, a comparable approach to the entropy method is followed. For this, a small weight is assigned to an attribute, that has low variance in the values across all alternatives. First, the standard deviation needs to be calculated

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^m \left(x_{ij} - \bar{x}_j\right)^2}{m}} \tag{151}$$

Then, the weights w_j are determined.

$$w_j = \frac{\sigma_j}{\sum_{j=1}^n \sigma_j} \tag{152}$$

Statistical variance weights

The statistical variance method presented in this section determines the weights through the statistical variance. For this, the statistical variance V needs to be calculated first, using the single performance values x_{ij} of the alternatives A_i and also the mean value $(x_{ij})_{\text{mean}}$ of all x_{ij}.

$$V_j = \left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(x_{ij} - \left(x_{ij}\right)_{mean}\right)^2 \tag{153}$$

Having the variance, the objective weights can be calculated through normalization as follows:

$$w_j^o = \frac{V_j}{\sum_{i=1}^{m} V_j} \tag{154}$$

Step-wise Weight Assessment Ratio Analysis (SWARA)

The SWARA method is carried out within five steps. First, the decision criteria need to be defined and ranked from best to worst by the decision maker based on their own experience. The resulting aggregated ranks are derived from the total scores. In the second step, the comparative importance of the previously set criteria is figured out while including the aggregated rank and the average of the comparative importances is calculated. Comparative importance in this case means the direct comparison between two neighboring criteria j. According to the outcome of step two, coefficients are assigned under the following conditions:

$$k_j = \begin{cases} 1 & if\ j = 1 \\ s_j + 1 & if\ j > 1 \end{cases} \tag{155}$$

Afterwards in the fourth step, each criterion's weight is assigned or calculated according to the conditions below, respectively:

$$w_j = \begin{cases} 1 & if\ j = 1 \\ \frac{w_{j-1}}{k_j} & if\ j < 1 \end{cases} \tag{156}$$

In the final step five if the calculation of the final weight q_j is determined via normalization as follows:

$$q_j = \frac{w_j}{\sum w_j} \tag{157}$$

Table 5: Weighting methods included in the review

Method	Acronym	Source(s)
Angular/Angle weights	-	(Shuai et al. 2012)
Criterion Impact LOS	CRILOS	(Zavadskas and Podvezko 2016)
Criteria Importance Through Intercriteria Correlation	CRITIC	(Diakoulaki et al. 1995; Tuş and Aytaç Adalı 2019)
Entropy weights	-	(Sałabun et al. 2020; Lotfi and Fallahnejad 2010; Li et al. 2011)
Equal/Means weights	-	(Sałabun et al. 2020)
Integrated Determination of Objective Criteria Weight	IDOCRIW	(Zavadskas and Podvezko 2016)
Methods based on the Removal Effects of Criteria	MEREC	(Keshavarz-Ghorabaee et al. 2021)
Standard Deviation weights	STD	(Sałabun et al. 2020; Wang and Luo 2010)
Statistical variance weights	-	(Rao and Patel 2010)
Step-wise Weight Assessment ratio Analysis	SWARA	(Stanujkic et al. 2015; Tuş and Aytaç Adalı 2019)

The review above showed that numerous MCDA and weight determination methods have been developed so far. Many of the methods described only differ in minor points such as the method to determine weights or additional in-between between-steps to normalized intermediated results during the MCDA process. The most important result of the review is that almost none of the methods is completely suited to fulfill the goal of having a simple way to perform an MCDA as it should be in the elaborated approach in this work. This is because many of the methods require large sets of data or detailed knowledge of the mathematical background. This results in difficulties for untrained users Due to that, a simplification of the AHP process will be pursued. As AHP already being a simple method, it is aimed to reduce the steps to be taken by directly validating intermediate results with real-world data without doing so as foreseen in the AHP process through consistency.

2.2 Land suitability

This section introduces the land suitability of certain areas for certain purposes, in this case, the land suitability for (irrigated) agriculture. The concept of land suitability and the influencing factors as well as the limitations are being explained. Additionally, some software, specifically developed for this purpose, is introduced.

In this discipline, the term "land" is used to describe an area of undefined size influenced by climate, topography, soils, hydrology, fauna, and anthropologic effects. Not included are socio-economic influences. (FAO 1976) In the further elaboration, the term "land" will be used in line with this definition.

Determining land suitability for whatever purpose ever is always a process of weighting different influencing factors to come to the perception if a certain area is suitable or not. Gaining knowledge on the suitability of land for a foreseen purpose is crucial to the success of the use itself, for example, financial investments might not be reached, or the needed agricultural yield might fail. Another effect making this evaluation necessary is the increasing dynamic in economic and population growth, leading to careless use of land, leading to environmental degradation (Rossiter 1990). In different studies, land suitability is not necessarily linked to agriculture. This could be, for example, the search for an estate for construction, groundwater, or nature protection zones.

The first approach to describe the process of land suitability evaluation was done by the Food and Agriculture Organization of the United Nations (FAO) through the widely referenced framework for land evaluation from 1976 (FAO 1976). This framework does not specifically target the agricultural sector but aims to generally support decision-making for any kind of land use, while the framework does not indicate for which purpose the land should be used but provides the information for the decision maker to simplify the decision-making process. Due to its nature, the framework, it is also called "shell" when mentioned concerning a knowledge-based system (Waterman 1986). Since the publication of the framework for land evaluation in 1976, several updates and expansions have been published, giving more precise instructions and examples for the different dimensions, specifically of agriculture as the framework itself does not do so. The officially called "guidelines" are available for rainfed agriculture (FAO 1983), irrigated agriculture (FAO 1985) and forestry (FAO 1984) as well as extensive grazing (Siderius 1984) and sloping areas (Siderius 1986). According to the first framework, land evaluation is only a part of the larger process of land use planning which stretches from the primary observation that a need for a change in the land use is necessary to the monitoring of the effect of the change.

New for this time was the introduction of the terms "Land Mapping Unit" (LMU), "Land Utilization Type" (LUT), "Land Characteristics" (LC) and "Land Qualities" (LQ) as well as the use of the term "land" as elaborated above. LMU are mapped homogeneous areas of specific characteristics. The exact definition of being a homogenous area lies in the responsibility of the decision maker and depends on the target of the research. It can be, for example, that an area is homogenous in its drainage properties but heterogeneous in present tree species, which might be irrelevant for the research. Land Characteristics are defined properties of the observed areas which can be unambiguously measured like slope angle, precipitation, soil texture, biomass of the vegetation, etc. Issues arise when the land is only evaluated by its characteristics, as some of them are interrelated with each other when specific processes are assessed. For example, the hazard of eroding soil depends on the land's slope angle, slope length, permeability of the soil, soil structure and the intensity of the precipitation. Due to this, the Land Qualities were introduced to tackle this issue. Land quality is an attribute of the land significantly affecting its suitability derived by the combination of land characteristics. The above-mentioned soil erosion hazard is an example of that. Others are, for example, nutrient availability, crop yields or workability of the land. (FAO 1976) Just as with the homogeneity of land mapping units, not all land qualities are important for each land potential land use that is examined. Lastly, the Land Use Type is the reference to the attributes of the land are compared. For example, a Land Use Type can be irrigated agriculture of sugar cane. Derived from previous research or literature review, the land characteristics and land qualities a land must have to be suitable for this purpose so that the land can be indicated as suitable. Land Use Types also include the socio-economic dimension, which is not part of the land characteristics and land qualities, which means necessary social or economic limitation and requirements need to be included in parallel through a separate process. (FAO 1976)

The framework indicated six principles to follow during a land evaluation process. The first suggests that the potential use for the land evaluated should already be considered during the process, since different requirements of different purposes, the land should fulfill in the future, severely affect the decision process. Secondly, the ratio of the inputs necessary to reach the desired benefits by the land use change needs to be determined. For example, in case the land would need large financial input to be suited for agriculture but the prospect revenues are low, it would be obvious that the land is less suited for this purpose. Additionally, every case needs to be viewed from different angles in a multidisciplinary approach so that certain aspects are not overseen due to limited observation by, for example, experts from the same field. The group doing the land evaluation should accordingly consist of natural scientists, technology specialists, economists, and sociologists. Combining all involved people's experience, the evaluation can be done, including all relevant physical, economic, and social aspects of the observed area. Another principle followed is the sustainability of the land use with focus on the conservation of the environment. So, if the potential new land use degrades or harms the land in the long period, even if it might be very profitable, it is assumed to not be suited for this use. Lastly, the last step of the evaluation is that different elaborated uses are considered for a specific area and the results are compared to each other if applicable and necessary. (FAO 1976)

To tackle and to automate land evaluation, many researchers tried to construct their own workflow and, in some cases, developed their own software to simplify the process. Some of these approaches and software will be explained in the following sections.

Automated Land Evaluation Systems (ALES)

ALES was introduced in 1990 (Rossiter 1990). This framework is used to guide knowledge-based land evaluation. Following the principles of the FAO's Framework for Land Evaluation, physical and economic suitability can be assessed through a digitalized workflow in ALES. Just as the FAO's framework, it is also just a shell, so for application it needs knowledge by the evaluation. Hence, this knowledge-based system can be referred to as an expert system (Rossiter 1990). Resultingly, following the terminology of (Burrough 1989) for quantitative models in land management, ALES is an empirical model while it is strongly influenced by the expertise of the applicant so it might also be labelled as "expert judgement model" (Rossiter 1990). As with every other model to evaluate land suitability, the issue of validation was emphasized by (O'Leary 1988) since practically observed, these models cannot be validated because for this, all the considered scenarios for potential land uses would needed to be tried out experimentally and the yields and financial revenues need to be compared. The only kind of validation that can be done is if the results are seen as plausible by the evaluator, or, as it was done in this study, the results are being confirmed because the land is already being used for the purpose resulting from the evaluation.

The ALES workflow begins with inserting information into the model, which can be plain facts like the length of crop cycles, environmental values like nutrients in the soils, topography and precipitation, or purchase prices. These factors' inferences should be combined through a decision tree to elaborate if the observed land is suitable or not. An example of such a decision tree was made in Figure 1.

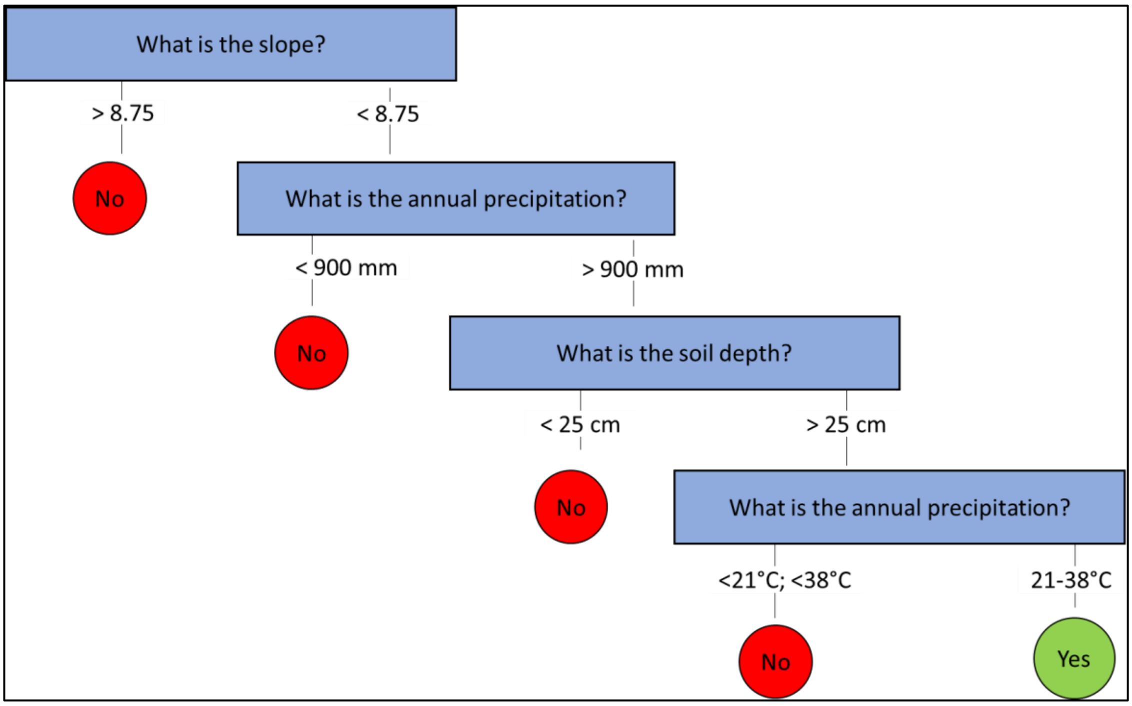

Figure 1: Simplified decision tree for the land suitability for sugarcane cultivation

An overall decision question needs to be formulated like "Is this area suitable to cultivate sugar cane?". In each level of the decision tree, a more specific question is asked (e.g. What is the slope?). In general, two connections are leading to the subsequent decision level labelled with the corresponding threshold to the question. In the example provided, the threshold would be 8.75°. If the slope of the observed area is steeper than 8.75°, the left connection must be followed, leading to the answer to the overall decision question "no". If the slope is below 8.75°, the connection leads to the next question and so on. If none of the specific questions had to be answered with "no", the overall question could be answered with "yes". It is possible to further adjust the decision trees structure by adding intermediate results, which allows the decision maker to subdivide the decision tree into several subprocesses. Additionally, the criteria targeted by the question in each level of the tree can be indicated as limiting or parametric. The term "limiting" in this case reflects the situation as described above, that if a question has to be answered with “no” the observed area is unsuited. Parametric means that if a “no” occurs, the area is not excluded per sé, but it will lower its suitability score towards other options.

Another advantage of ALES is that since it is a knowledge-based system, so-called annotations can be added to the model components (i.e., decision levels) to explain why the model has been set up the way it is or to provide a literature reference, the decision was built on (Rossiter 1990). A disadvantage of ALES is that it generally does not include the economic dimension. This dimension can be still included, however, as from the land quality resulting from ALES, the estimated yield can be derived for which the gross margin can be calculated with the local market prices of the crops. From this revenue, annual expenses can be subtracted to calculate the profit.

Land Evaluation using an Intelligent Geographical Information System (LEIGIS/ISLE)

This approach is available under two different names in the literature, meaning the same. The first “An Intelligent System for Land Evaluation (ISLE), the second is Land Evaluation using an Intelligent Geographical Information System (LEIGIS). For the purpose of this thesis, “ILSE” will be further used to describe this approach. ISLE introduces the graphic visualization of land suitability using Geographic Information Systems (GIS) and is a ready-to-use software. ILSE can be divided into three parts: The front end, the digital map, and the expert system. The front end is a software typical user interface allowing the user to navigate through and apply the software. From its functions, the digital map resembles today’s common online map services, which allow the user to display an area of choice, zooming in and out, and to add basic structures like highlight areas. The map also contains a geographical database to provide information and any characteristic of the observed area. The expert system contains the knowledge base of this method. Compared to the FAO framework, however, this knowledge base is preset and cannot be edited by the decision maker. (Tsoumakas and Vlahavas 1999)

LIMEX

LIMEX is an interactive multimedia imaging system which was developed for the purpose of increasing yield of lime farms, especially in the areas where the primary language is Arabic. Because of that, the user interface is available in English and Arabic. The software can assess the land suitability of a certain area, disorder diagnosis, and recommendation for irrigation and fertilizer application. (Mahmoud et al. 1997)

Land Evaluation Computer System (LECS)

Based on the FAO framework, a team from the FAO Centre for Soil Research in Indonesia developed a computer system for land evaluation in 1983 (Wood and Dent 1983). The aim of LECS was to build a simple model using the already available data or those kind of data which are easy to obtain. As a result, LECS outputs the local crop yield from which inferences can be drawn to the land suitability. The considered physical parameters are the eight land qualities: temperature regime, water regime, nutrient retention, nutrient availability, salinity, toxicity, and rooting conditions. The 14 land characteristics, also physical parameters are the average monthly temperature in the growing season, the length of the growing period in days, the annual rainfall in mm, the cation exchange capacity in me/100 g, the contents in nitrogen, phosphorus and potassium in kg/ha each, the salinity in mmhos/cm, the rooting depth, the drainage class according to (Soil Survey staff 1951) and the texture class according to (Sys and Riquier 1980). Additionally, the pH value is considered at three different times in three different ranges for corresponding levels of quality. LECS operates in two stages. First, the potential productivity of an area is evaluated for the crops included in the process for three different levels of technology and management input. Additionally, the soil degradation is assessed applying an adaptation of the universal soil loss equation. This adaptation calculates the loss of soil for different land uses and compares the resulting loss with the tolerable soil loss in the area. The difference defines the necessity of conservation measures for the different land uses. In the second stage, the economic dimension is included by determining the potential productivity for the three different technologies and management levels mentioned in stage one. These levels depend on the input of (financial) resources, cropping patterns, and available (financial) resources for conservation and land improvement. The amount of monetary input for conservation comes from the need of the recommended conservation measured resulting from stage one. The results of stage two are crop-specific recommendations based on economic factors.

LECS has the advantage, that it can display its results in many different ways. For example, already after stage one, the areas which are affected by each crop constraint can be displayed and summaries can be provided, which areas and their respective sizes were assigned to which class. The weaknesses of this approach are that LECS does not include irrigation measures or the use of the observed land for livestock. It is mentioned, however, that due to the modularity of the database of the method, the requirements for such purposes might be included in further development steps if necessary. (Wood and Dent 1983)

Vegetable Expert System (VEGES)

VEGES is a multilingual expert system introduced by a consortium of researchers from the Agricultural University of Athens, Greece (Yialouris et al. 1997). The system targets specific greenhouse agriculture in the Mediterranean region for vegetables and aims to identify the most common pests, diseases, and nutritional disorders of the cultivated crops. Since the number of all possible pests, etc. was considered as too large, this restriction was done. The intent of the system is to fill the gap of low-cost high technology software for low technology greenhouse management. VEGES is based on a previous, simpler version called AUA.ES which only focused on diseases affecting tomatoes. VEGES instead considered six different crops: Pepper, lettuce, cucumber, bean, tomato, and egg-plant. For the diagnosis of the pests, diseases, and nutritional disorders, the system needs accurate descriptions of the symptoms the plants show, like leaves developing red or purple tints, older leaves die prematurely, or failure to form a heart, which all would indicate phosphorus deficiency. The knowledge base with which the descriptions are compared has been generated through consultation of six experts for the region. The software is available in English, Greek, French, Italian, Spanish, Portuguese, and Turkish.

Mediterranean Land Evaluation Information System (MicroLEIS)

The MicroLEIS, or MicroLEIS DSS (=Decision Support System) as the name indicates is a an agro-ecological system to support sustainable land use planning developed by a consortium of researchers from the Institute of Natural Resources and Agrobiology of Sevilla, Spain (La Rosa et al. 1992) specially for the areas under Mediterranean conditions. The system combines both observational and experimental information and is alike others following the FAO Framework for Land Evaluation (FAO 1976). The method does not consider social and economic attributes like capital intensity, labor cost, farm size or land tenure and has no spatial reference. The latter means that each observed area is evaluated independent from its actual geographical location. (La Rosa et al. 1992) The system is performed in different stages. In the first stage, the general land capability is determined considering the location, soil limitation, erosions risks and bioclimatic deficiency which can be derived from basic data like slope, soil depth, soil texture, drainage, salinity, share of coarse fragments slope and soil erodibility, rainfall erosivity and vegetation density as well as rainfall and frost risk. (La Rosa and Mafaldi 1982) The capability results are divided into four classes S1 – Excellent, S2 – Good, S3 – Moderate, and Class N – Marginal and Not Suitable. This stage gives information on whether the observed land is generally suitable for agriculture independent from crop requirements or economic aspects. The second stage is split into two possible paths. The stage 2a is the process of determining the agro soil suitability which includes reference values for twelve typical Mediterranean crops (wheat, corn, melon, potato, soybeans, cotton, sunflower, sugar-beet, alfalfa, peach, citrus and olive) and assigned the suitability classes S1 – Very High, S2 – High, S3 – Moderate, S4 – Low and S5 – Very Low to the observed sites depending on their present values for the criteria. The criteria examined for this stage are the effective depth, texture, drainage, carbonate content, salinity, sodium saturation and the degree of profile development. Stage 2b in contrast focuses on the forest land suitability. Again, a number of typical species (22) is selected as reference. The criteria examined are the latitude, the altitude, the physiographic position, the soil depth, texture, drainage, pH, the mean minimum and maximum temperatures of the coldest and warmest months and the annual precipitation. Depending on the outcome of this stage, the sites are only classified as S – Suited or N – Not Suited for specific species. After the split-up stage 2, only for stage 2a, there is a succeeding stage 3, while the process ends after stage 2b. The reason is that the subsequent stage 3 estimates the crop yield, which is not applicable for forestry. In stage 3, the useful depth, clay content, depth to hydromorphic feature, carbonate content, sodium saturation and cation exchange capacity are considered and fed into a pre-developed statistical model by the authors in a previous research (La Rosa et al. 1981). The model also included interactions between the criteria, like the relation between clay content and cation exchange capacity. The results are estimated yields for the considered crops in kg/ha. (La Rosa et al. 1992)

Agriculture Land Suitability Evaluator (ALSE)

ALSE is a method combining GIS and MCDA components to determine the geo-environmental land suitability for agriculture in (sub-)tropical regions and is also based on the FAO framework for land suitability. (Elsheikh et al. 2013) A newly introduced property of this method is that a database with factors to consider when evaluating land for a specific purpose is included, and how to do it. In its structure, ALSE can be divided into three parts. The first part is the visual interface to represent the evaluation results and to draw conclusions or necessary edits to be done in the evaluation process. The second part consists of the data table in which, for example, new crops and their respective requirement can be added to extend the number of considered crops. The third and last part is the ArcMap Model Builder, a tool in the GIS ArcMap to develop models in a simple and easy to follow way. (Elsheikh et al. 2013) The method developed includes six tasks, which have to be performed: Crops selection, climate, soil, topography, evaluation, and records manager. The first four tasks required entering data or selecting criteria to include in the evaluation, the latter two are execution and results display parts. For each of the criteria, choices have to be made from pre-defined options. For the crop, for example, land characteristics and land qualities need to be selected. For the climate, the annual precipitation and the length of the dry season need to be indicated. For the soil criterion, the nutrient availability, nutrient retention, rooting conditions, soil workability, and oxygen soil drainage need to be indicated. For the topography, the possibility of future mechanization is measured by indicating the slope in degrees. The suitability evaluation is the execution task, which starts when the user chooses the crop to use as reference for the evaluation. In the record manager, the outputs of the evaluations are listed in the shape of database tables. This gives the user the possibility of editing the data for improved visualization in GIS.

The further process to display the results is performed in five steps. First, the five input datasets with which the model runs need to be standardized and combined. For this, the two vector datasets soil and slope are joined and the results of the previous suitability evaluation are entered in the data table. In the second step, the joined shapefile is converted into raster files, then the weighted overlay is done. The resulting overlay raster reflects the suitability of the area. In step three, the values, i.e., the raster, need to be classified into the five suitability classes S1, S2, S3, N1, and N2. Here, S1 is the best suitable class and N2 the least suitable class. Afterwards, the raster suitability file is converted back into a polygon vector file. Lastly, this vector file is processed in a way, so that the initial information on the parcel shapes is applied in the vector file, to that the suitability information resulting from the process can now be retrieved for each of the parcels which initially should be evaluated for their suitability. (Elsheikh et al. 2013)

Land Suitability Evaluator (LSE)

Another tool was developed by (Nguyen et al. 2015) at the Vietnam Academy of Science and Technology in 2015. The approach is divided by the author into four steps to perform. First, the characteristic which should be considered in the evaluation needs to be defined. Between these, it must be distinguished between factors and constraints. In this approach, the factors and constraints are divided into three groups: ecological aptitude, environmental impact and socio-economic feasibility. For all of these, different physical and socio-economic characteristics need to be assigned, which directly have an impact on the suitability of the land observed. While doing this, focus needs to be laid on the availability of measured data for these characteristics. In addition, information on locally cultivated crops and their requirements and expert knowledge on the study area needs to be available. The decision whether the chosen characteristics count as a factor or constraint is based on the nature of the characteristics. If it is a crisp distinguishable Boolean indicator with sharp boundaries allowing a clear statement whether the land is suitable or not, the characteristic is a constraint. An example for a constraint is the land cover. If the observed land, for example, is covered by a water body, it is not to be discussed if this land is suitable for agriculture or not, as it clearly is unsuitable. (Nguyen et al. 2015) There are, however, exceptions to this rule imaginable. An example for such exceptions would be a desperate need for additional land leading to the possibility of drying out certain areas like it was done in the Netherlands. Characteristics which are considered as factors on the other hand are more likely to be changeable, like soil fertility, which can be increased by fertilizers. The factors can also be indicated as limiting and non-limiting, which has sort of a resemblance to the Boolean constraints. If a factor is considered as limiting, the area is marked as unsuitable from the beginning, marked unsuitable if the values are ranged outside the suitable values. As mentioned above, the decision whether a characteristic is seen as a factor or as a constraint lies within the responsibility of the decision maker. In the second step, the corresponding requirements towards the land use are formulated and value ranges are assigned. The ranges are determined based on expert knowledge and empirical measurements in the area. As in previous research, certain value ranges for the factors are assigned to different suitability classes: S1 – High suitability, S2 – moderate suitability, S3 – marginal suitability, and N – unsuitable/ not suitable. As mentioned above, the Boolean constraints are only indicated as S – suitable or N – unsuitable/ not suitable. These, however, only reflect the suitability under current conditions without potential development of the observed area. The values ranges should be determined in two sets per crop or cropping pattern. One being the value ranges for optimal growth and the second for minimal growth. Afterwards, the evaluation criteria are converted into scoring functions so they can be combined with the score of each observed parameter. To do so, the values need to be standardized first. The authors suggest performing a linear scale transformation at this place. Resulting in values between 0 and 1. In the third step, the characteristics are arithmetically combined to generate so-called partial performance indices in a GIS-based MCDA approach. This is done by bringing all the factors and constraints in uniform raster files of the same resolution and extent, and using the constraints as a mask layer to exclude all N cells. Due to the Boolean nature of the constraints, only the cells of the areas considered as suitable remain. In the last step, the partial performance indices are classified regarding their aptitude, impact on the land suitability and the feasibility classes. This is done based on expert knowledge and/or on empirically derived results on the relation of value ranges of the indices and the results yields of the cultivated crops. The suitability classes are chosen as above. This results in the overall land suitability classes indicating the quality of the observed land, which is done in two steps. First, the environmental impact of the land use and the agro-ecological aptitude are combined to reflect both their inputs to the land suitability or suitability class towards the overall suitability class. For example, if the environmental impact equals S1 – Very suitable or N – unsuitable/not suitable, the agro-economical aptitude is evaluated as the same. If the environmental impact is rated as S2 or

S3, the agro-economical aptitude is lowered by one or two classes. Secondly, the long-term degradation of the natural resources is taken into account as the software implies unsustainable and soil depleting agricultural practices to reflect future development of the land suitability under reasonable conditions. This leads to decreasing land suitability for future predictions. (Nguyen et al. 2015; Nguyen et al. 2020; Thanh et al. n.d.)

Limitations of Land Suitability evaluation

During the early phase of this research, it became clear that there are several limitations and problems to handle. The major issue was data availability. Other than in developed countries, where spatial data like annual precipitation, slope, soil texture, nutrient contents, etc. are openly accessible, this is not the case for countries in the third world, especially for remote areas. Even if data is available, it either is outdated, or where a series of data sets are necessary, like for climate-related data, the time series are not long enough or have data gaps. Additionally, if data is available, it might not have the necessary accuracy, meaning that regarding raster data, such data, mostly if recorded and provided, has the cell size ranges in the km^2 dimension, while in the developed countries, the cell size is normally 1 m or less.

Another factor not limiting the result of land suitability evaluation but the reliability of the results is that some properties of the land can be changed, which lead to less good evaluation results. For example, lacking nutrient contents, especially for nitrogen or phosphorus, can be easily compensated with fertilizers, less precipitation can be compensated with irrigation, or too steep slopes can be converted into terraces. There are, however, some methods for the land suitability evaluation available that include such improvement potential, but most of these are very complex and not considered as very user-friendly and easy to use.

Lastly, some factors from a technical perspective simply cannot be considered but are still crucial to the land suitability. An example highlighted in the literature is biologic parameters like microbial biomass, respiration, mycorrhizal associate, nematode communities, enzymes, and a more detailed characterization of organic matter, since all these underly dynamic processes, which cannot be quantified in a generalized way (La Rosa et al. 2004).

2.3 Water Resources Management in Agriculture

In this section, Water Resources Modelling (WRM) in general and its different dimensions are being explained. In specific, WRM in river systems is focused on current challenges and developments in this area. This includes irrigation techniques, the software “Aquacrop”, and water transnational water distribution conflicts, as well as an introduction into cropping systems.

Cropping Systems

The concept of cropping systems was introduced by (Sébillotte 1974) in the context of traditional French agricultural research, but was still further developed in the subsequent years. (Leenhardt et al. 2010) The concept was developed for a homogenously farmed area combining several components building the cropping system, which are crop succession, cropping pattern, and crop management techniques (Bégué et al. 2018). For the crop succession, there are three different approaches available: Monoculture, Rotation cropping, and Fallow cropping. Aside from the typical understanding of monocultures being large areas where only one crop is cultivated over a period of several years, according to (Franco et al. 2022) It could also mean that crops are only predominantly cultivated in certain regions but no monoculture is pursued as in the first interpretation of the term. The advantages of monoculture are that different water or nutrient requirements do not have to be considered, and also in case there is one crop which brings significantly higher revenue than other crops, the maximal economic benefit can be achieved. On the other hand, monocultures are more vulnerable towards pests, weeds, and diseases, and due to the ongoing not changing nutrient withdrawal, the soil fertility decreases over time, leading to shrinking revenues. (Haneveld and Stegeman 2005). To reduce this effect, the natural recovery of the soil would need to be supported by adding either organic or chemical fertilizers. This, however, bears a financial obstacle for small-scale farmers and also would increase their workload because of the additional work to apply the fertilizers. (Tanveer et al. 2019)

In the crop rotation approach, a predefined set of crops is systematically planted in different plots. After one growing cycle, the plots will be filled with a different crop from the set in a predefined sequence. This step is repeated after each growing cycle until the crop planted in the first place "reaches" the respective parcel again. The main idea of this approach is to conserve the soil fertility by planting crops with different requirements so that the soil can recharge itself until a certain crop is planted again. Through this, the yield and therefore the revenues remain on a constant high level. For effective crop rotation, the crops need to be carefully selected and knowledge about their nutrient and water requirement needs to be available. A rule of thumb for the selection is that in general, no crops of the same botanical family (for example pumpkin and zucchini) should be successively planted in one parcel. Additionally, during determining the order in which the crops are planted, it should be considered when the precipitation is high so that water-intensive crops can be planted during this period. (Tanveer et al. 2019)

The last crop succession method is the fallow cropping, which might be considered as a derivative of the crop rotation. This method is very common in the semi-arid, and arid regions of West Asia and North Africa. (Nielsen and Calderón 2011) In fallow cropping, one parcel is left uncultivated (=fallow) for a specific period of time to allow the soil to regenerate itself (Ryan et al. 2008; Sanchez 1999). Even if the parcel is unused from a typical agricultural perspective, there are different ways it can be left fallow. Bare fallow, for example, is done when the parcel is still free of any weeds growing and pests that might evolve. There are subdivisions of bare fallowing depending on the effort made and tillage done on weed and pest removal. If only external work is done, like the application of herbicides, fungicides, and insecticides, it is referred to as no-tillage. The other extreme is the maximum tillage approach in which the parcel is intensively plowed and harrowed. A certain amount of tillage can be useful to achieve mixing the upper soil layers with crop residues on top of the soils as well as it brings more oxygen, water and microbes in lower soil layers resulting in organic matter mineralization with is beneficial for the recovery of the soil fertility and the reduction of the growth of perennial weeds. (Thomsen et al. 2015; Nielsen and Calderón 2011) The main disadvantages of the previously described approaches are that due to the application of chemical additive, the risk for pollution of the adjacent water source, like surface and groundwater, increases and that intensive tillage deteriorates the soil's natural structure and increases its erosion potential. (Blanco-Canqui and Lal 2008) Weed growth, however, can also be beneficial for the farmer if the bare fallow is pursued, because they could serve as feed for livestock in the winter and spring months (Ryan et al. 2008). Another option is to cultivate pulses in the parcel, which are in the fallow period as pulses can be used for crop production but also adds nitrogen to the soil, improving its quality again. Having the soil covered with plants instead of leaving the bare soil for a long time, this approach protects the soil from drying out, erosion, improves water intake, and reduces evaporation. (Nielsen and Calderón 2011; Ryan et al. 2008)

The cropping pattern is the second part of a cropping system. A cropping pattern describes an advanced crop succession plan, a temporal and spatial plan to cultivate different crops to achieve the maximum yield. The difference between the two is that the crop succession only refers to a specific time span in one year, while the cropping pattern can span over several years. Cropping patterns also reflect the proportion of land areas under different crops at a particular moment (Sun et al. 2015). Cropping pattern can be categorized into two types. The first is the single cropping in which only one crop is considered per area per year, is chosen. The second type is the multiple cropping, in which several crops are cultivated simultaneously. Besides the number of crops, the difference between the two is that if more than one crop with different growing cycles is cultivated, there can be more than one harvest in one year, which is especially important to have a constant food supply or a constant income if the crops are sold on the market. Cultivating, multiple crops at a time, a more complex system of sequential and intercropping can be developed to create synergies between parallel growing crops and also to recover soils while continuing agriculture, for example through planting pulses to increase the nitrogen content of the soils as mentioned above (Bégué et al. 2018). For intercropping, there are different ways to apply in terms of several crops, as it is possible to have double or triple cropping. Other derivatives are mixed cropping, strip cropping, row cropping or agroforestry. In mixed cropping, as the name indicates, the different plants are randomly mixed on the field. In strip intercropping, the plants are arranged in blocks of the same plant in alternating order with small rows in between. In row cropping, there are now blocks of the same crops as in the strip cropping but only single rows of alternating crops. A visualization of the methods described can be seen in Figure 2. Lastly, agroforestry is the overall term for perennial plants of woody nature like trees or shrubs. These are often combined with herbaceous plants and livestock. The relay cropping is a type of sequential cropping where the crops are planted in such a temporal distance to each other, so that each growing phase of the crop is occurring on the field. When the crop is ready to be harvested, the next crops will be planted immediately on those areas. By following more effective multiple cropping methods, the productivity of the cultivated land increases and depending on the exact method (e.g. sequential relay cropping), continuous harvesting can be done and through diversifying the crop selection crop failure can be compensated by the remaining ones (Mahlayeye et al. 2022; Tigre and Heshmati 2023). Increasing productivity could lead to sufficient yields so that further expansion of agricultural land and therefore required deforestation to gain this would be unnecessary. Other advantages are that due to the diversity in the spreading of pests, weeds and diseases, it is overall reduced, and because of the regularly occurring tillage, it is also less likely that they outlast more than one season. A side effect of this is reduced costs as less fertilizers, pesticides, insecticides, and fungicides need to be applied. (Azam-Ali 2003; Bégué et al. 2018)

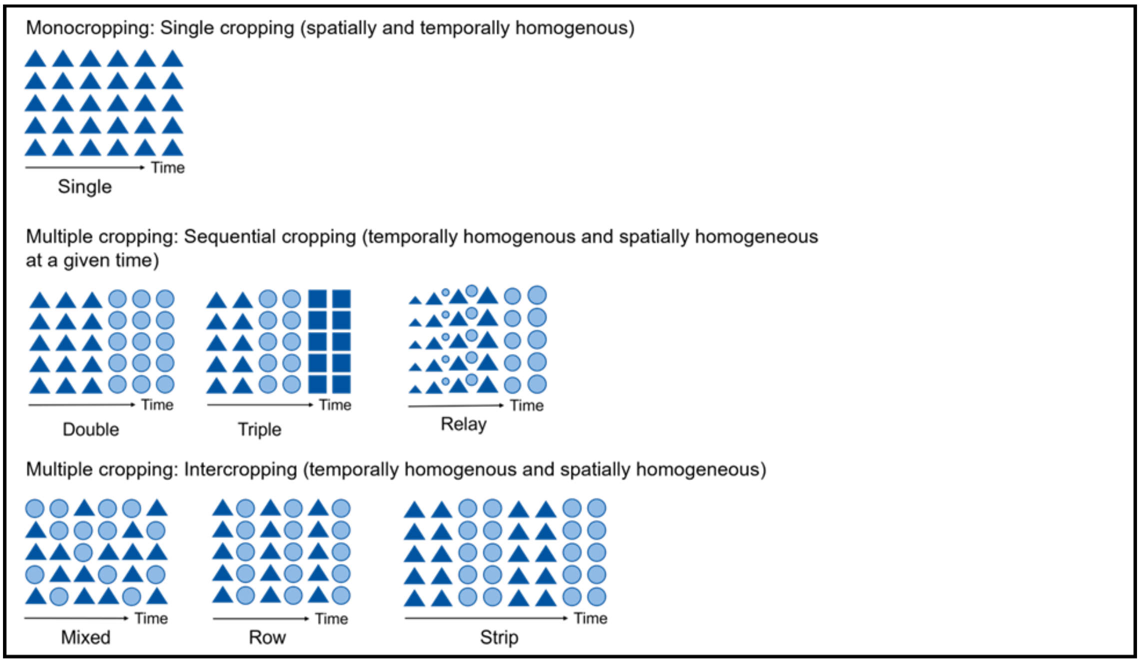

Figure 2: Examples for the different cropping patterns according to (Mahlayeye et al. 2022)

The third component of a cropping system are different crop management techniques, which describe how the farmer is cultivating his land, what decisions he or she makes. Examples are specific practices which are performed for harvesting or after the harvesting has been done, like leaving the leafy materials of the harvested materials, which are not the crop on the field for fertilization. Others are the crop selections for cultivation, if, how, when, and which fertilizers, pesticides, fungicides, or insecticides are used. The specification of the irrigation systems, if it is applied, also belongs to this component. As different irrigation techniques are a crucial part of this research, this topic will be described in detail in the upcoming section.

To ensure high productivity of the agriculture, the described components, crop succession, cropping pattern, and crop management techniques need to be taken equally into account. The alternative to match the growing population's increasing demand for food, to increase the area of cultivated land, which is the case in most parts of the world (Shiferaw et al. 2011). In many areas, however, the expansion of agricultural land is not possible due to different reasons like lack of arable land, unsuitable climatic conditions or technical restrictions.

Irrigation

A key method to improve the productivity of agriculture, especially in arid or semi-arid countries or in countries with rain and dry seasons, is irrigation. Especially in these regions, where rainfed agriculture might only be possible for some months, irrigation would double or even triple the productivity depending on the chosen crops. Another use case for irrigation is to support rainfed agriculture by only adding the deficit between water intake from precipitation and the optimal water supply to maximize the yields or to bridge over short-term water deficits to avoid water stress of the plants (Reddy 2010). In this section, focus was laid on furrow, sprinkler, and drip irrigation as these are the ones considered for the determination of the irrigation water demand in the case study.

Numerous different irrigation methods exist, of which some only show minor differences but belong to both an overarching group of methods. The first distinction between the methods is made if it is pressurized, like sprinkler and drip irrigation, or gravity-based like flood or furrow irrigation. Moreover, methods showing certain similarities are grouped, like it is the case for furrow, basin/flood, or border irrigation, which both belong to surface irrigation. In some cases, the irrigation method to be chosen is limited by the availability of water, electricity, or the physical appearance of the farmland. For example, if the farmland has slopes, surface irrigation methods would not be applicable. The basin/flood irrigation, as its name indicates, is done by flooding the whole field, like it is well known for rice fields. In the border irrigation, only channels surrounding the field are filled with water so that it can percolate horizontally with the water gradient in the soil. Lastly, the furrow irrigation makes use of the same effect, but here, the water channels are constructed in between the planted rows to better reach the plants. The surface irrigation methods are the most common applied ones as they are easy to set up and operate, and do not need much financial input (Yadeta et al. 2022). Usually, the furrows are constructed using machinery like tractors or ridger, but in some cases they are done manually as well. Whether this step is done before or during the sowing process depends on the farmer's decision. At the end of the channels, they can either be blocked or attached to a drainage system. For optimal operation, all channels should be parallel and at least be five meters deep so that no unregulated flooding can happen. (Brouwer et al. 2001) Of course, depending on the estimated discharge in the channel, the specifications might change. While the main advantage of this method is the low costs and easy construction and maintenance once it is set up, the method has very low water use efficiency due to seepage and evaporation losses (Brouwer et al. 2001; Abou Seeda et al. 2020).

From the two, closely observed pressurized systems, the sprinkler irrigation has a precipitation-like water application. Like for all pressurized systems, the water is distributed from a basin through a system of valves and pipes in case of the sprinkler system, then to the sprinklers, which spray the water in a circle-shape over the field (Brouwer et al. 2001). Depending on the condition, different types of sprinkler irrigation systems are available, like center pivot systems, in which many sprinklers are mounted in a linear row, which is connected to the pivot point and rotates around this point. Through this method, the typical circle-shaped farmlands occur. The size of the systems and the number of sprinklers depends on the size of the field and the need of the farmer. The simplest center-pivot system would be the automated traveling gun as it is also known from sports grounds or lawn watering. (Scherer 2005, Revised 2022) Sprinkler system, since there is a pressurized bare high cost for initially installing and then operating the system, also due to ongoing electricity costs. Because of the man parts like pipes, valves, nozzles, etc., the system is also vulnerable to clogging, which prevents proper water outflow and requires skilled maintenance personnel. The water is distributed as vapor, and is very prone to evaporation losses. The advantages of the systems are that the field itself does not need to be prepared in any way, like it needs to be for surface or drip irrigation, and that besides clay soils, all other soil types are suitable for this method. Additionally, since the system itself requires less to no space on the field itself, except for sporadically left free space for moving tracks, since the pipes run above the field. This leads to practically more area on which crops can be cultivated compared to other irrigation methods, in which areas of the field have to be allocated water channels, for example. (Stauffer and Spuhler 2011)

The last considered method is the drip irrigation, also referred to as trickle irrigation. Just as sprinkler irrigation, the drip irrigation is a pressurized system containing many components to distribute the water. A difference to most sprinkler systems is that it is mostly permanently constructed and not supposed to be moved due to the large installation efforts. Using this method, small water pipes are distributed in fields alongside the planted row with having one single outlet for each plant, which are called emitters or drippers. A typical flow rate ranges from 2-20 l/h. Regarding soil and crop type and slope of the field, the method does not have any restrictions and so is universally applicable. It is possible to lay the pipe on top of the surface and underneath close to the rooting zone of the plants to maximize the water use efficiency. This also creates optimal conditions for the plants, as a continuous and constant water supply is provided. The method, due to its high technical standard, is very effective and hence can save large amounts of water compared to other methods. This is due to deep percolation, surface runoff, and evaporation being minimized. Due to its direct and efficient outreach to every single plant, the addition of fertilizers can be considered through the irrigation systems as well. This approach saves cost for wasted inaccurately applied fertilizers and also reduces the salinization of the soils. The disadvantages are that because of the high-tech nature, the system is very expensive in the installation, which has to be done before any revenue happens. Additionally, the difficult system requires skilled personnel, even though the system runs automatically during the growing seasons, but must be adjusted for new plants and also to solve problems that might occur. The most prominent is clogging, which describes the blockage of the outlet through soil particles, roots or residuals from fertilizers, which are directly distributed with the irrigation water. (Brouwer et al. 2001)

To estimate the cost of the three methods, it is important to take different farm sizes into account. Example data is provided in Figure 3 provided by the FAO and based on data from the Ethiopian Ministry of Agriculture (MoA). The data includes costs for the construction parts exemplarily for the administrative regions Oromia, Amhara and Tigray in Ethiopia. The data was structured between the three methods, and also if the application area is in the highlands or the lowlands. Since some structures like pumps or reservoirs require the same financial input for small-, medium- or large-scale farms, the costs were provided for 5 and 50 ha farms. Other literature suggests an average investment cost for the construction of an irrigation system to be about $4,000 per hectare which shows resemblance with the values for sprinkler irrigation in Figure 3 (Diao et al. 2005; Inocencio et al. 2005).

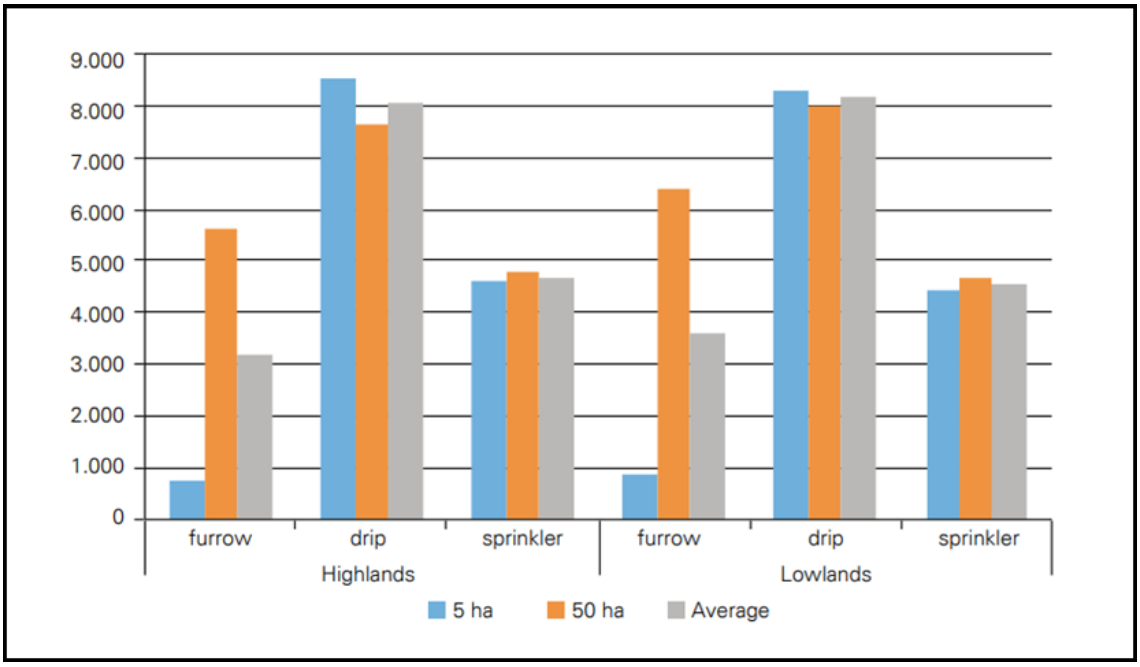

Figure 3: Surface water irrigation - Average unit investment cost in USD/ha (Mendes and Paglietti 2015b)

Irrigation Scenarios

Aside from the method which is used for irrigation, it is important to differentiate between the irrigation scenarios in terms of intensities. The approaches included in this research are the full irrigation and supplemental irrigation, which will be further described. In general, full irrigation is referred to irrigation that happens throughout the whole year. Supplemental irrigation is only done when previously specified situations occur, like impending water stress. (Wale et al. 2019; Nangia et al. 2018) Other than that, exact definitions of these scenarios are not available and, in some cases, it is not clear to indicate the transition from supplemental to full irrigation. This especially is the case for months in which the precipitation already covers the water requirement of the plants. For clarification, the definition of the two scenarios applied in this research is as follows: Supplemental irrigation is designed to provide only the amount of water necessary for the plant to survive on a basis of monthly water demand. Full irrigation ensures that the plants receive the water, which is necessary for the optimal plant growth, also on a monthly basis.

AquaCrop

To support the process of allocating water resources, the FAO developed an irrigation simulation tool called "AquaCrop". The software can derive the water demand of agriculture considering the effects of evapotranspiration and water loss due to infiltration in deeper soil layers. (FAO 2017a) The software by intention has low requirements from both computational and input data perspectives. The primary user interface of AquaCrop is divided into two sections. In the section "Environment and Crop" information on the climate, the observed crop, the management, and the soil need to be indicated. For the climate, it is possible to access the FAO database "CLIMWAT" to obtain the necessary climate data. Due to that, even local climate zones like those used in the case study could be included. CLIMWAT for its part is part of the software "CropWat", also by the FAO. CropWAT specifically focuses on irrigation planning for different crops under consideration of climate data from a series of weather stations. (FAO CLIMWAT 2025) The information retrieved from CLIMWAT includes data relevant for the water demand while cultivating crops like reference-evapotranspiration and evapotranspiration rates of the plants chosen, soil evaporation, minimal and maximal temperatures, precipitation, annual mean CO_2-concentration and soil water content. Temperature and precipitation values can be retrieved daily, for periods of ten days or monthly. For the CO2-concentration time series data from 1902 until today is used. This also allows to make predictions for future development regarding the CO_2-concentration and so depict increasing CO_2-concentrations due to climate change. For some cases, measured values for the evapotranspiration are not available. In this case, a tool to calculate the evapotranspiration based on other climate data is included in AquaCrop. For the information, on the crop, the user can select amongst a comprehensive database with the source included. The data for the crop includes the length of the growing cycle. The start of the cycle has to be manually selected so that it fits into the proposed cropping pattern if applied. Under the management section, the aspects of type of field management and irrigation management are summarized. Field management indicates which level of mechanization is present on the field in terms of machinery, for example. For irrigation, the specific method (for example flood, furrow, pivot, sprinkler, drip, subsurface irrigation) needs to be indicated to take losses due to seepage during water evapotranspiration losses into account. Conveyance losses depending on the chosen irrigation method are not considered. If no indication is made here, the software assumes that rainfed agriculture is done. It is also possible to evaluate existing irrigation plans. For doing so, information on the starting point of the irrigation measure after the day of sowing, application depth, and water quality need to be entered. The starting point gives insight, when to irrigate and the depth gives insight how large when the soil moisture storage is and based on the water requirements of the selected crops also when it is empty or better said the specific wilting point of the currently cultivated crop is reached and need to be refilled with a specific amount of water until the field capacity is reached. For the soil section, information on the soil profile and the available groundwater resources can be indicated. For the soil profile, any typical soil types can be chosen in the easiest approach. It is also possible, however, to indicate the exact shares of sand, silt, and clay in the soil, and the bulk density of the soil and the porosity of the soil in relation to its overall volume. The Bulk density in this case is assumed to be equal to the soil in its natural state without human interference. There are sets of data for the different texture classes available to choose in AquaCrop, if, however, they do not match the specific case to study, up to five soil layers can be manually added. If no choice is made for the groundwater, the tool assumes that no shallow groundwater table is available. In the second part of the user interface, the framework of the simulation can be set. Possible inputs here are the simulation period, where the starting and the ending point are indicated. The initial condition for example of the soil water content can be set, as well as if off-seasons where no agriculture is undertaken and the soils could recharge should be included. Lastly, a project in which the results should be stored in can be indicated as well as additional observations done on site if applicable.

The output of AquaCrop can be subdivided into different progressive parts. First, the canopy cover is simulated to gain knowledge on the overall growth of the crop. Differently described, the canopy cover reflects the share of the soil which is not reached by direct sunlight anymore. The minimal canopy cover, which is always zero percent, is located at the moment of sowing, the maximum during the middle of the cropping season. The maximal value, however, does not necessarily need to be 100%, but still, this could be the case depending on the circumstances. The canopy cover gives insight into whether the crop had to face water stress during the growing cycle, which might lead to a reduction of the canopy development. Additionally, from the expansion curve of the canopy growth, conclusions can be drawn on the root development of the plants. Secondly, the transpiration of the plants is simulated by multiplying the reference-evapotranspiration with the plant coefficient. Since the plant coefficient is proportional to the graphs of these two parameters have parallel developments, the results throughout the life cycle of a plant. Another correlation effect is that if water stress might occur, which would affect the canopy growth, the plants would also close their stomata, which leads to reduced transpiration. In the third step, the biomass above the surface is calculated in tons per hectare. While doing so, AquaCrop automatically considers potential weed infestation, soil fertility and salinization of the soil as well. The fourth and last step is the calculation of the yield, which is done using specific harvesting indices for every crop. The indices reflect the share of the previously calculated biomass, which is the actual crop. (FAO 2017a)

Although the software is very promising and easy to use. The problem lies in the unique database necessary for certain application areas. For example, for the study areas observed in the case study during this research, not all data for the plants chosen for the study, which are sort of unique, are included in the database. Additionally, the software does not assess spatial data but only punctual locations and also does not reflect conveyance losses during irrigation, which can make up to 40% losses in the worst case (FAO 2023b). Due to that, the software could not be used although it would have immensely simplified the process.

3 Study area

3.1 Introduction

Ethiopia is the second largest populated Country in the African Continent after Nigeria (UN 2019). Irrigated agriculture is expanding in Ethiopia in parallel to the rapid population and economic growth. Agriculture represents 35.45% of Gross Domestic Product (GDP) in 2020 (World Bank 2020). The agricultural sector is also the largest contributor of work and income with approx. 85% of Ethiopia's population (Nigussie et al. 2019; Nasir et al. 2019; Gebregziabher et al. 2013). At the same time, agriculture is by far the largest consumer of water resources with 9.69 Billion Cubic Meters (BCM), which accounts for 91.86% of the total surface water usage while municipal water withdrawal accounts for 0.81 BCM and industrial water withdrawal accounts for 0.05 BCM (FAO 2017b).

Agriculture in Ethiopia is normally carried out in flat areas, either in the Ethiopian Plateau or the lowlands. The crops are chosen based on the availability of rainwater. While 85% of the precipitation in Ethiopia is occurring in the rainy season from June to September (Awulachew 2007; Awulachew et al. 2010; Belay and Bewket 2013), the primary cultivated crops are cereals at this time (Makombe et al. 2007). Supplementary irrigation is necessary for higher value cash crops such as pepper, tomatoes, onions, potatoes, or other vegetables (Nigussie et al. 2019; FAO 2020). The availability of irrigation water throughout the year could enable cultivating crops for two or even three seasons, not only during the rainy season (Awulachew 2007). To increase the water storage capacity, generate hydropower, and make more water available for agriculture as well as other activities, the Ethiopian government is intensively constructing dams on the course of different rivers. For example, the Ethiopian government is planning to build a cascade of four dams along the Blue Nile river, the Nile's largest tributary (Awulachew 2007). The first major dam, named Grand Ethiopian Renaissance Dam (GERD), was started to be built in 2011 and was supposed to be completed in Summer 2020 (Basheer et al. 2018). The remaining three dams called Beko Abo, Karadobi and Mandaya are still in the early planning phase. Hence, only basic information is currently available (Samaan 2014).

Traditional irrigation has already been used in Ethiopia for ages and is currently applied in about 60% of Ethiopia's irrigation area, but has not changed since then (Nile Basin Initiative 2009). Most traditional schemes follow basic methods like surface irrigation fed by diverted surface water, hand-dug wells or developed springs. The canals for the water distribution have to be renewed after every flooding since they are made from local material. Although there is an advanced version of this method where the canals could be lined with concrete, which implies lower seepage losses, the low irrigation efficiency and high evaporation losses of this method remain the same (Makombe et al. 2007; Nile Basin Initiative 2009). Some of these Modern Small-Scale Irrigation (MSSI) schemes already include micro dams for temporary water storage. These dams increase the use of harvested rainwater to increase the available water for irrigation out of the wet season in late summer. (Nile Basin Initiative 2009) However, the current data shows that out of the 55 million ha of estimated arable land in the Blue Nile Basin, only 40% is currently cultivated (Awulachew 2005; Werfring et al. 2004) and only around 5% of the potential irrigated areas is developed (Worqlul et al. 2015).

Irrigation development is one of the major development strategies of the government of Ethiopia. (Makombe et al. 2007) It plays a crucial part in sustainable development and the reduction of poverty. (Nigussie et al. 2019) A vast amount of proposals for small-scale irrigation developments shows how development in this sector is important for the Ethiopian government. (Makombe et al. 2007) In 2010, Awulachew et al. and the International Water Management Institute estimated that there is around 30 to 70 million ha of cultivable land in Ethiopia from which about 15 million ha is under cultivation. Current irrigation schemes cover approximately 640,000 ha out of 3.7 million ha of total potential irrigable land (excluding irrigation through rain water harvesting practices). Multiple case studies of river basins in Ethiopia provided the data on existing irrigation schemes, commonly applied irrigation techniques, and cultivated crops which were used as reference to set up a realistic and comparable framework for this study. Their main focus is on medium and large-scale irrigation development with no rain water harvesting practices. Instead, diverted surface water from nearby rivers is mainly used. Table 6 summarizes the irrigation potential in Ethiopia.

Table 6: Irrigation potentials for the different catchment areas in Ethiopia

Basin	**Catchment Area [km²]**	**Irrigation potentials [km²]**			
		Small scale	Medium scale	Large scale	Total
Abay	198,890.7	458.56	1,303.95	6,393.30	8,155.81
Tezeke	83,475.94	N/A	N/A	833.68	833.68
Baro-Akobo	76,203.12	N/A	N/A	10,195.23	10,195.23
Omo-Ghibe	79,000	N/A	100.28	579.00	679.28
Rift Valley	52,739	N/A	40.00	457.00	1,393.00
Awash	110,439.3	305.56	245.00	790.65	1,341.21
Genale-Dawa	172,133	18.05	284.15	10,445.00	10,747.20
Wabi-Shebele	202,219.5	107.55	559.50	1,712.00	2,379.05
Danakil	63,852.97	23.09	456.56	1,108.11	1,587.76
Ogaden	77,121	N/A	N/A	N/A	-
Ayisha	2,000	N/A	N/A	N/A	-
Total	**1,118,074.53**	**912.81**	**2,989.44**	**54,844.97**	**37,312.22**

An estimate of an additional 1.6 million ha of potential irrigable land can be added by considering rainwater harvesting practices and groundwater as water sources. (Birhanu et al. 2015; Awulachew et al. 2010) Motivations for the exploitation of the agricultural production potential of the country are the achievement of food self-sufficiency at the national level, the generation of foreign currency from export earnings, and the satisfaction of the raw material demand of local industries (Birhanu et al. 2015). The topography of the Upper Blue Nile River basin has two significant features: the highlands, ragged mountainous areas in the central and eastern part, and the lowlands in the western part. Altitude ranges from 498 m in the lowlands, e.g. Sudan border, to 4,261 m in the highlands, e.g. Mount Guna. According to Ministry of Water, Irrigation and Electricity (MOWIE), about two-thirds of the basin area fall in the highlands, where elevations range from 1,500 to over 4,000 m and a slope greater than 25% is present. In the lowlands, elevation drops down to approximately 500 m and the slope is lower than 7%. The topographic characteristics of the basin together with the near-equatorial location of the UBNR basin have a significant effect on the water resources distribution as well as the rainfall pattern in the basin (Awulachew 2007).

Mountains are limiting agriculture in many developing countries. At least 12% of the world population is currently living in mountainous areas, of which 80% lives below the poverty line and 37.5% suffers from food insecurity (Roozitalab et al. 2011). Therefore, mountain agriculture is considered important for enhancing food security (Roozitalab et al. 2011) and eradicating poverty in different developing countries. Steep slopes and easily erodible soils complicate low-tech agriculture in such areas (Mekonnen 2019; Messerli et al. 1990; Lal and Stewart 2010; Tamene and Vlek 2008). However, these challenges do not necessarily prevent agriculture. Many examples worldwide for successful mountain agriculture are available, such as the cultivation of wine in Europe (Conedera et al. 2004), rice on artificial terraces in China (Yuan et al. 2014; Adachi 2007), maize, cereals, and potatoes in Peru and Bolivia (Zimmerer 1999) and terrace-based agriculture in North Africa and the Middle East, which already happened 3000 years ago (Valipour et al. 2020). Even in Ethiopia, the cultivation of plants in mountainous regions is not new. Previous assessment of change occurred in the land-use and land cover in the past century, indicated an increase in the agricultural areas at the cost of forest areas in the mountainous regions (Hailemariam et al. 2016). For example, the cultivated land increased from 1957 to 1995, between 75 and 400% depending on the investigated slope class. The comparatively higher increase could be observed in the steeper area due to easier accessibility and cultivation with progressing mechanisation of agriculture in Ethiopia (Zeleke and Hurni 2001). The crops chosen for cultivation in the newly developed, steeper agricultural areas do not differ in a noticeable way from the popular crops in the previously cultivated, flat topographical areas, but mostly are reduced to basic cereals or potatoes (Simane et al. 2013).

High population pressure, high erosion hazard, loss of forest reserves and declining per capita food production have led to the need to establish improved, sustainable farming systems in the Central Highlands of Ethiopia. The Ethiopian's five-year agricultural development strategy (1998-2002) aimed to increase agricultural production. Production must be intensified to counterbalance the available food and the growing population. The main objective of irrigation is to allow for double cropping seasons. Irrigation on a small scale has been practiced for a long time. Low river flows in the dry season limit the irrigation projects. Therefore, the basic idea is to store part of the 72% annual runoff that occurs during July-September for subsequent use (African Development Fund 2004).

The assessment of surface water irrigation potential in the Ethiopian highlands conducted by Worqlul et al. (Worqlul et al. 2015) has shown that the availability of water presents the main limiting criteria. The study determined land suitable for irrigation first, then quantified the river water availability during the dry season. Weighted criteria that affect the irrigation potential of a land area were used to determine land suitability. The criteria chosen are rainfall, evaporation, soil type, land use, slope, market access, and proximity to a perennial river. The availability of water from October to May during the dry season was determined by the analysis of long-term discharge records of the four main rivers in the Lake Tana basin. The study concluded that irrigated agriculture is mostly hindered by the lack of available water and therefore the potential for agricultural expansion can be considered as high in the investigated areas if the amount of available water would increase (Worqlul et al. 2015).

To estimate the agriculture potential in the Blue Nile scheme, land suitability for agriculture in general and for irrigated agriculture in particular needs to be assessed. Therefore, the objective of this research is to assess the potential of agriculture extension based on irrigation in the Blue Nile River basin in Ethiopia. This estimation will be based on assessing the land suitability for irrigated agriculture depending on a set of assessment criteria.

3.2 Physical and climatic characteristics

The Blue Nile Basin is located in the northwest of Ethiopia as shown in Figure 4. The study area is mainly hilly and mountainous terrain of the Ethiopian plateau, except for the lowlands in the north-western area near the Ethiopian-Sudanese border (Johnson and Curtis 1994). In this study, the two rivers, Dinder and Rahad, located in the north-west of the catchment area, are included within the study area since they join the Blue Nile after the Sudanese border (Awulachew 2007; Abtew and Dessu 2019; Negm and Abdel-Fattah 2018). The Blue Nile originates from Lake Tana in the Ethiopian highlands. After flowing 1.450 km, the Blue Nile merges with the White Nile in Khartoum to form the main Nile. The Ethiopian Blue Nile contributes up to 60% of the Nile flow while covering only 10% of the Nile Basin drainage area (Arsano and Tamrat 2005; Negm and Abdel-Fattah 2018). The elevation of the watershed ranges from 500 to 4261 m showing a diverse topography.

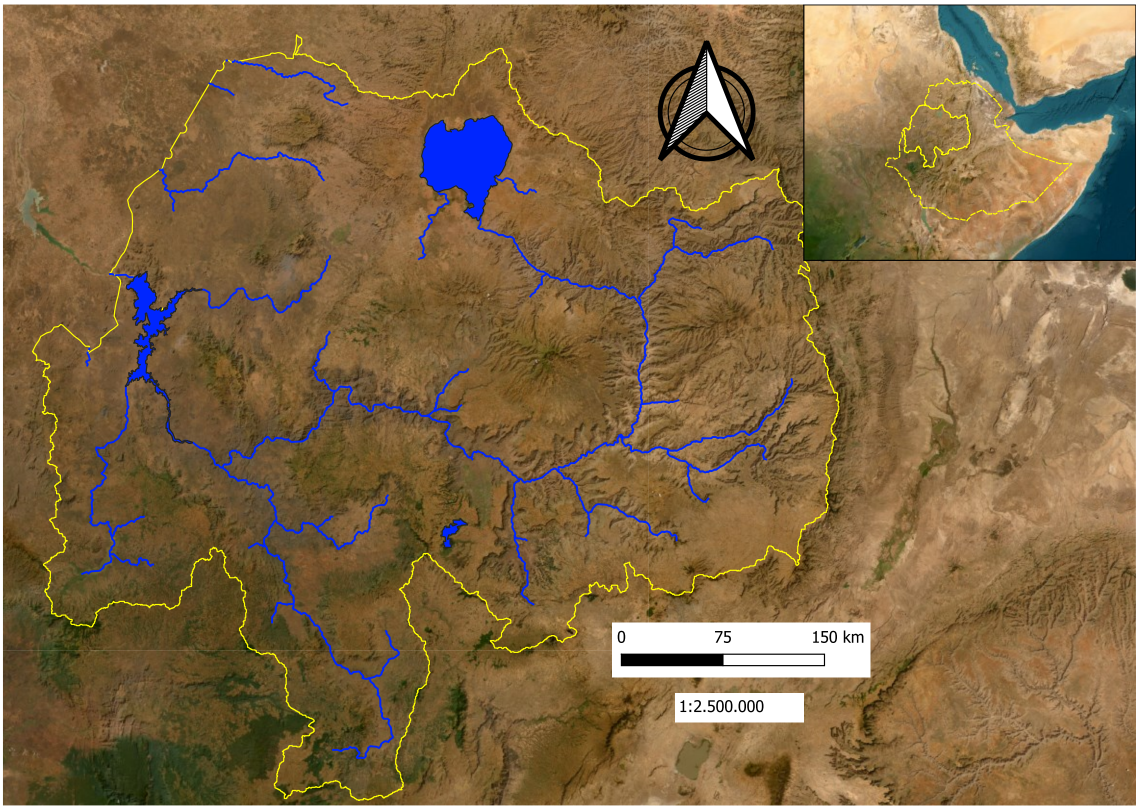

Figure 4: Overview Map of the study area in Ethiopia

According to the elevation data from (Worldclim 2022a), derived from the SRTM elevation data, the slope ranges from flat areas to 60% with 44% of the basin covered by less than 5% land slope. 24% of the basin is covered by highland slopes above 20% with rugged and undulating land surfaces of non-uniform topography (Awulachew 2007).

The climate in Ethiopia and the Blue Nile Basin is mostly regulated by altitude as the country is in tropical latitude. A distinction is made between five agro-ecological climate zones; the cold high mountain zone (called Wurich, above 3,200 m), the cooler high altitudes (Dega, 2,300 - 3,200 m), the temperate, densely populated zone (Weynadega, 1,500 - 2,300 m), the hot zone (Kola, 500 - 1,500 m) and the hot desert areas (Berha, below 500 m). All five climatic zones exist in the Blue Nile Basin with mostly Dega and Weynadega on the plateau and Kola along the Sudanese border. (Abtew and Dessu 2019) The average annual temperature in the Blue Nile Basin ranges from 7°C to 28°C. It is expected that due to the climate change, the temperature in the Nile Basin will rise by 1.5-2.1%, which means that almost the entire Nile region could be covered within the next 30–40 years to become an arid to semi-arid region (Negm 2018; Worldclim 2022a).

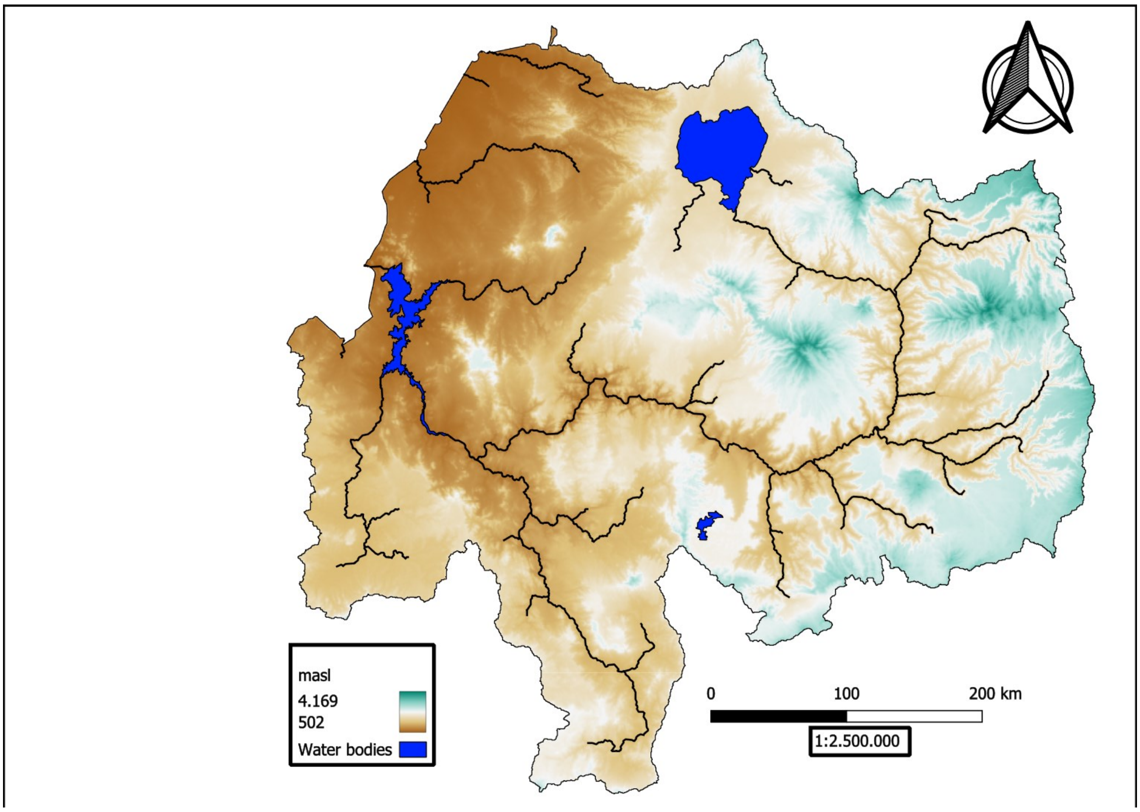

Figure 5: Topographic Map of the Blue Nile Hydrologic Catchment Area

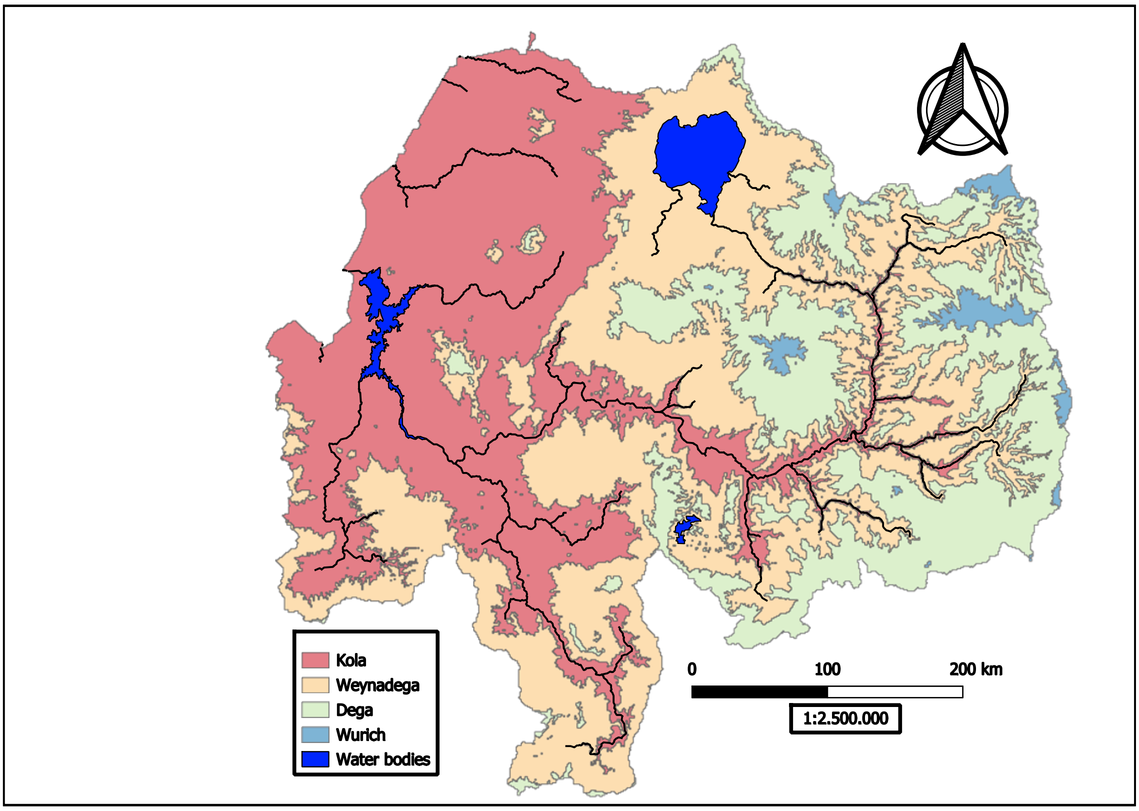

Figure 6: Climatic Zones of the Blue Nile Hydrologic Catchment Area

In the study area, there is a minor rainy season in April and May and a major rainy phase from June to September during which approximately 74% of the annual rainfall occurs, which is estimated to be 1,423 mm. Due to the high seasonal variability of rainfall, the flow of the Blue Nile fluctuates with the timing and amount of rainfall. The maximum runoff in August is 60 times more intense than the minimum runoff in February. Based on the annual rainfall and the corresponding river discharge, the Blue Nile basin is the wettest part of Ethiopia (Abtew and Dessu 2019; Arsano and Tamrat 2005)

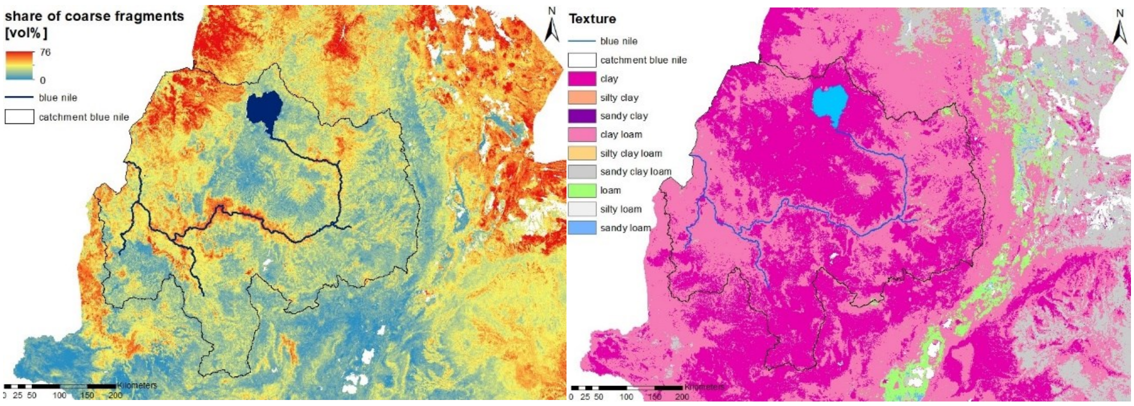

Figure 7: Share of course fragments (a) and soil texture (b) in the study area

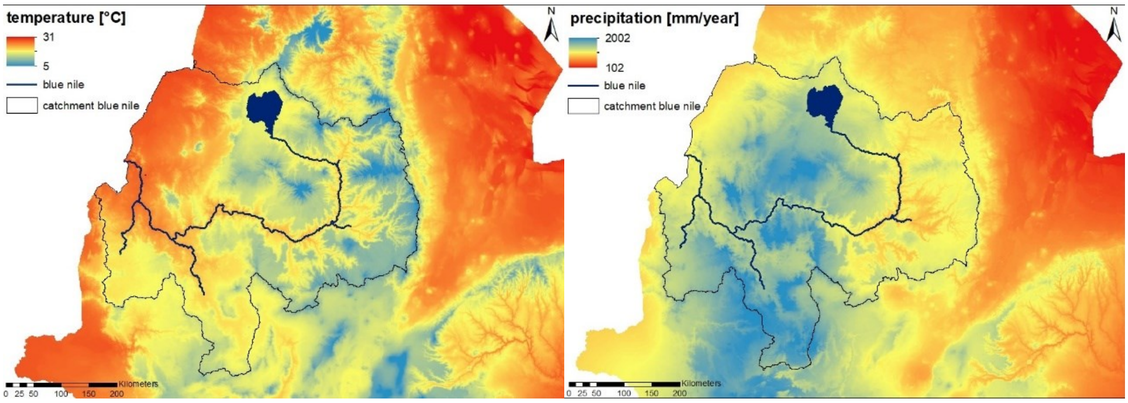

Figure 8: Average annual temperature (a) and precipitation (b) in the study area

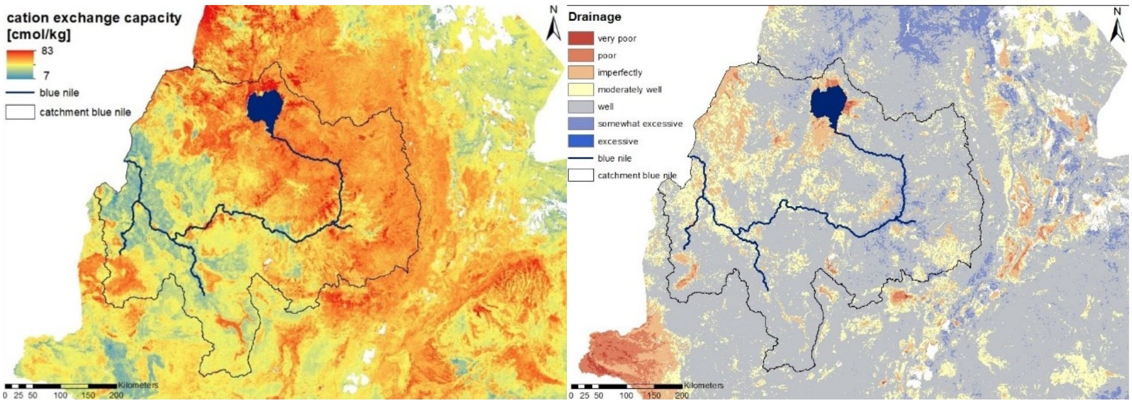

Figure 9: Cation Exchange Capacity (a) and Drainage Properties (b) in the study area

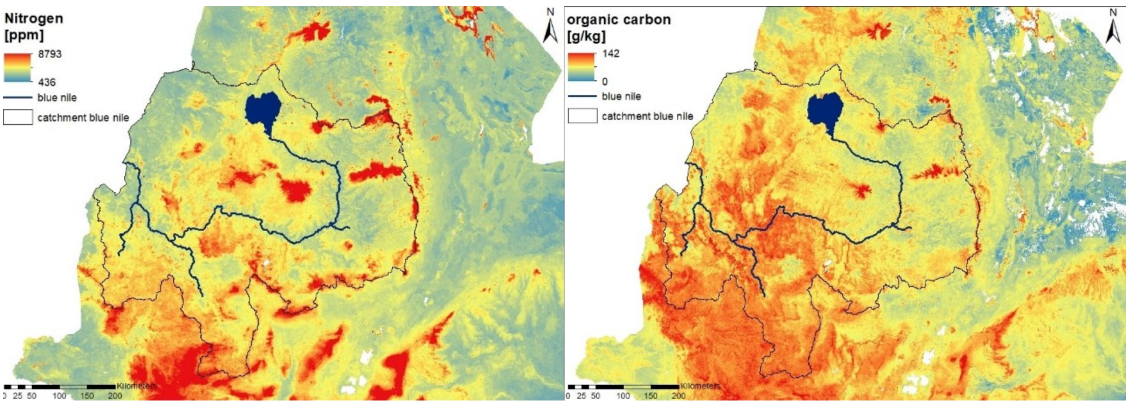

Figure 10: Nitrogen content (a) and Organic carbon content (b) in the study area

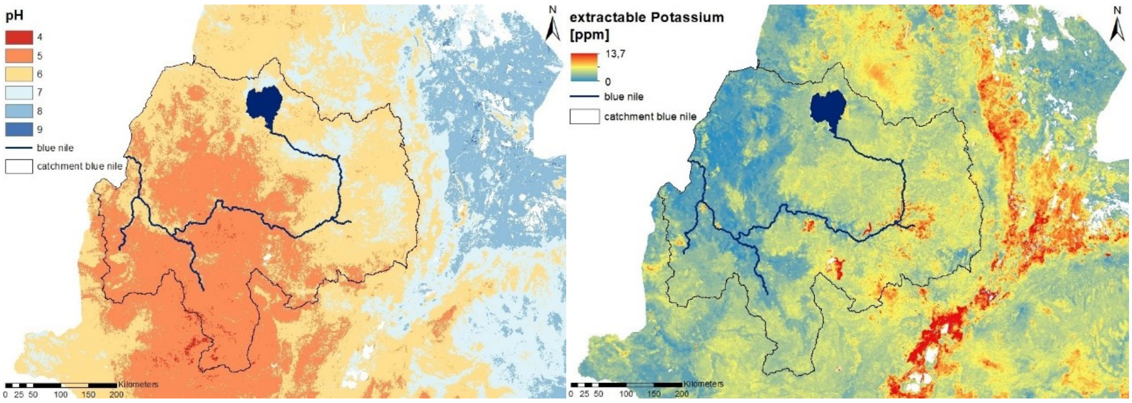

Figure 11: pH values (a) and Extractable Potassium (b) in the study area

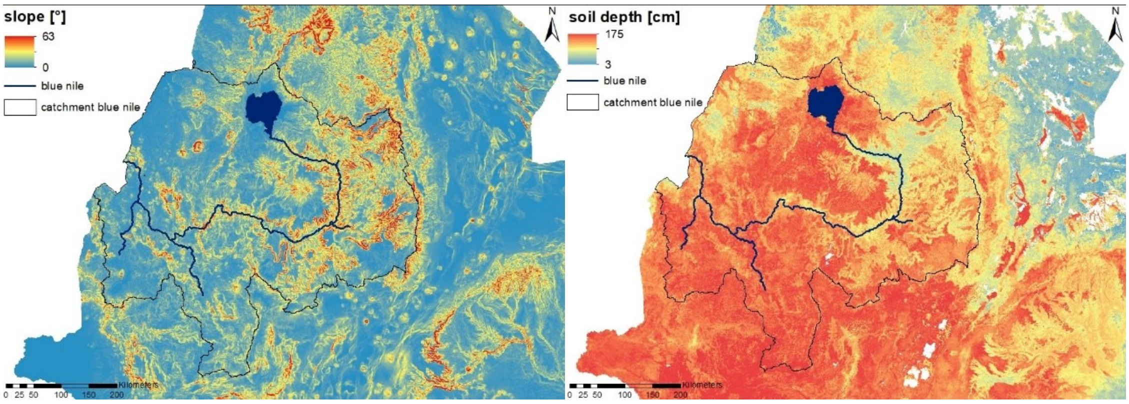

Figure 12: Slope (a) and Soil depth (b) in the study area

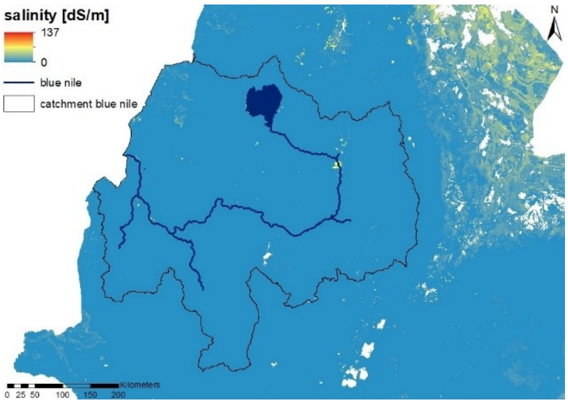

Figure 13: Salinity in the study area

The mean annual flow of the Blue Nile River at the Ethiopian-Sudanese border is estimated to be about 49 BCM with a range of year-to-year variation. (Nile Basin Initiative 2009) According to the Harmonized World Soil Database (2009), the Blue Nile Basin is mainly covered with clay soil as shown in Figure 7b.

The present clay soils can be divided into two subtypes; the vertisol soils with high content of swellable clay minerals, which also cause poor drainage properties of the soil (see Figure 9b) and the red clay loam soils in the sites with better drainage properties in areas with moderate slopes and high precipitation.

Concerning the land cover of the Blue Nile Basin, almost the entire highland area is farmland covering 33.9% of the basin. Grassland, being the other major highland land cover with 23.1%, occurs primarily either in poorly drained depressions or on level and exposed high-altitude locations. Finally, woodlands, bush and shrubs cover 20.3% and 10.2% of the Blue Nile Basin area and the forest cover is about 1.41% with most of the forest remnants remaining in the south-west of the basin. (Abtew and Dessu 2019) In addition to drought, flooding and soil erosion, deforestation is one of Ethiopia's greatest ecological problems. Due to the significant population growth and the resulting expansion of agriculture, large parts of Ethiopia's forest cover have been cleared over the last 50 years to create agricultural land or for firewood. Within 100 years, the proportion of forested land in Ethiopia has fallen from 40% to 2-3% (LIPortal 2020; Zeleke and Hurni 2001).

3.3 Socio-Economic and Political status

By the time of this dissertation, the inhabitants of Ethiopia account to 123 million people on an area of approx. 1.129 million km^2 (Statistisches Bundesamt 2023). Ethiopia is the second most populous nation in Africa after Nigeria and is considered as one of the fastest growing economies in the East African region with an estimated growth in the financial year 2021/2022 of 6.4% (The World Bank Group 2023). Despite this good economic trend, which started about 15 years ago, resulting in decreasing poverty rates, Ethiopia still ranks as one of the poorest countries in the world (The World Bank Group 2023). Based on the 2020 Water Atlas developed by the Abbay Basin Development Office approx. 32.9 million people are living in the Blue Nile Basin, which is expected to increase in the upcoming years to approx. 40 million based on information from the Central Statistics Agency (CSA) and the Amhara National Region State Bureau of Finance and Economic Development (ANRS BoFED) (Ferede et al. 2020). By this time, the population in the Blue Nile Basin would make up around 32% of Ethiopia’s total population based on the overall population development forecast provided by the German Federal Statistical Office of 150 million inhabitants in 2030 using Data from the United Nations Population Division (Statistisches Bundesamt 2023).

Accompanying population growth, the productivity in the economic, agricultural sector in whole Ethiopia is rising as well. The agricultural production tripled between 2000 and 2020, and a share of 34% of Ethiopia’s land area was used for agriculture. (Statistisches Bundesamt 2023). As a rather poor country, 84% of the population works in the agricultural sector. This circumstance is also reflected in the export revenue of 42% of Ethiopia’s GDP, which is generated from exporting agricultural goods. This already indicated the importance of this sector for the further development of the country. (The Federal Democratic Republic of Ethiopia 2022a)

Even though the majority of Ethiopia’s population is working in the agricultural sector, food shortages occur from time to time, leading to the necessity of food aid, which is steadily increasing. (Kedir 2021) The shortage can be traced back to several biotic and abiotic factors such as lack of technical progress, soil degradation, environmental disasters like floods and droughts inefficient use of water resources, and socio-economic crises like the recent Ethiopian civil war from 1974 to 1991, the Ethiopian civil conflict which started in 2018 and is still ongoing or the Covid-19 pandemic in the early 2020s. (World Food

Programme 2023; Yigezu Wendimu 2021; White 2005) One way to make farmers less dependent on seasonal fluctuations is the implementation of irrigation. So far, only around 5% of farmers have irrigated their fields, leaving the other 95% heavily dependent on rainfall and exposed to a high risk of losing their yield in times of droughts. (Rapsomanikis 2015; Gelete et al. 2020) Another factor which increases the likelihood of food shortages is that the majority of farms are categorized as smallholder farms (Taffesse et al. 2011), which precludes subsistence overall subsistence agricultural structures, which are vulnerable to the above-mentioned factors since no safety mechanisms or financial reserves are in place like for large commercial farms. Commonly, there is no distinct definition available to which area, crop output or revenue a farm counts as a smallholder farm. If a characterization is done in other research, it is mostly based on the cultivated area. (Rapsomanikis 2015) The (CSA) defines smallholder farms as farms with less than 25.2 ha cultivated area and large commercial farms, vice versa. (Taffesse et al. 2011) In other literature, the threshold value is set lower to 2 ha in general and specifically 0.9 ha for Ethiopia. (Rapsomanikis 2015) According to the FAO however, smallholder farms cultivate areas up to 10 ha. (FAO 2012) To bring this into context, the average size of large commercial farms is 323 ha. (Taffesse et al. 2011)

As mentioned above, the main difference between the types of farms is their size. Independent from this, small scale farmers are cultivating their crops for their consumption rather than for local or international selling purposes. The habit of small-scale farms also differs from large commercial farms as they are often disseminated over larger areas, while the latter ones are mostly contiguous areas. Small-scale farms also lack access to the markets due to also lacking modern farm management practices like the use of fertilizers, technology, irrigation, improved seeds, and plant protection products. In conclusion, this leads to lower yields and therefore also lower profits that larger farms achieve. (Taffesse et al. 2011; Boere et al. 2016) This framework results in the inability for the framers to improve their situation as more financial resources are necessary for these modern techniques, seeds, etc., to achieve higher profits or to build up reserves for years with small yields. (Yigezu Wendimu 2021; The World Bank Group 2021) Still, 95% of the crops produced in Ethiopia have their origin on small-scale farms. (Mendes and Paglietti 2015a)

Due to the dependency of Ethiopia on natural resources, it is one of the countries which is most vulnerable to climate change. Inducing longer periods of droughts on one hand and intense floods through heavier rainfall compromise food security to a large extent. The combination of these extremes also leads to dryer soils in the beginning and increased erosion of the soils when the heavy rainfalls occur. Previously mentioned population growth and food demand combined with increasing risks for crop failure due to climate changes, adaptation strategies have to be developed, especially by small-scale subsistence farmers.

3.4 Existing Agriculture in the Blue Nile Basin

Agriculture in the Blue Nile Basin is mainly traditional rainfed cultivation. Nevertheless, especially in the upstream reaches of the Blue Nile Basin, the trend of using small-scale irrigation is increasing (Abtew and Dessu 2019). Ethiopia has a wide variety of crops, the most common being cereals (maize, sorghum, wheat, teff, barley, millet, etc.), pulses, oilseeds, herbs and spices. In addition, fruit, vegetables, sugar cane, fibers (e.g. cotton), as well as root and tuber vegetables are cultivated. The cultivation and harvesting time of the individual crops depends on the season and climatic factors (Deressa 2007; FAO 2010).

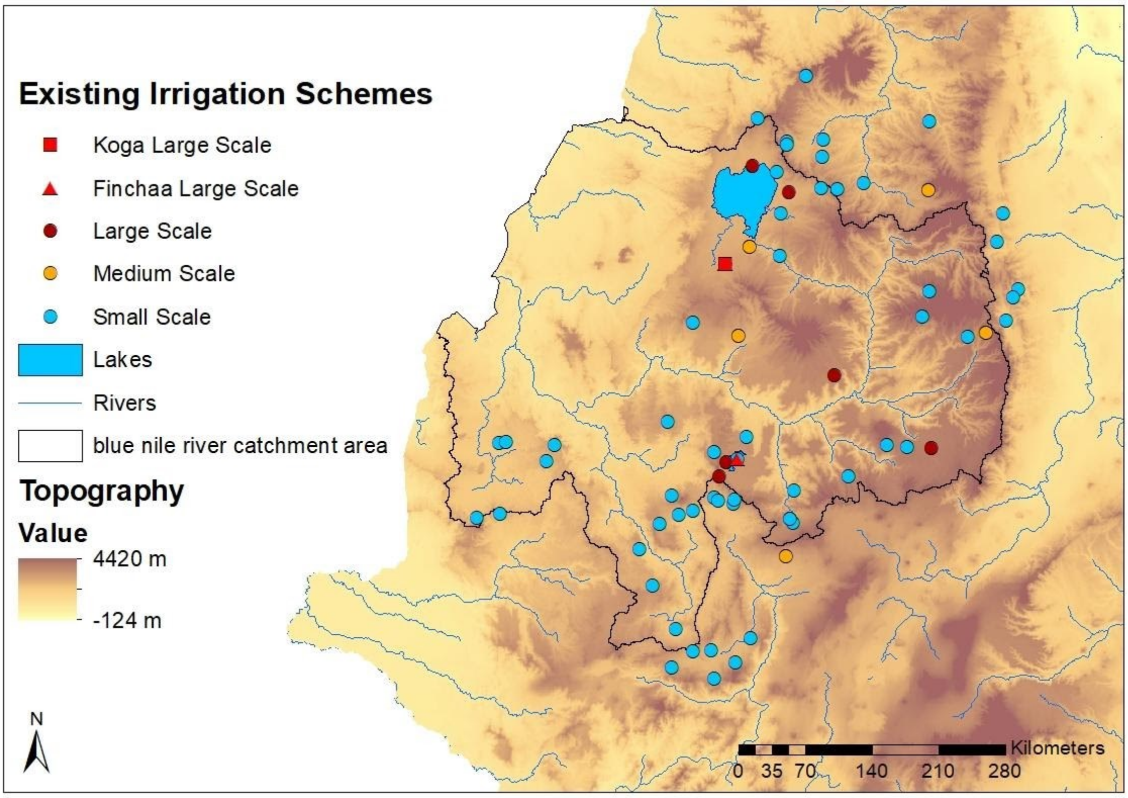

Figure 14: Existing irrigation schemes in the Blue Nile Basin and adjacent area

A central point in this area is the Lake Tana basin. The surrounding farms grow one crop per year during the rainy season (Worqlul et al. 2015; Awulachew 2007; Awulachew 2009; Belay and Bewket 2013). Considering the total area of the Blue Nile basin, only a small share of the area is irrigated. Irrigated farms in the uplands mostly use surface water irrigation, while irrigated farms in the plains use groundwater (Worqlul et al. 2015). Most other agricultural activities in the Abbay river basin are similar. However, because of the large and diverse area of the basin, different agricultural and water harvesting practices can be found.

Nigussie et al. (2019) have quantified the surface water availability from January to May, during the dry season in the Jabitenan district in the Blue Nile basin. They employed the Soil and Water Assessment Tool (SWAT) to evaluate land management practices, discharge, sediment transport and nutrient cycling through simulating the hydrologic cycle for one Hydrologic Response Unit (HRU). Land suitability for irrigation was assessed by using the Multi-Criterion Decision Evaluation (MCDE) method in the Geographical Information System. It was mostly based on soils, topography, and proximity to the nearest stream. The study shows that the irrigable land was mainly limited by the available water resources (Nigussie et al. 2019). They recommended water harvesting strategies to provide agriculture with irrigation to increase productivity. McCartney and Girma (2012) found that the average irrigation demand per ha has an increasing trend as the result of changes in rainfall and potential evaporation. They determined an annual average irrigation demand of the catchment of 8,244 m^3/ha from 1983-2021. The results of the simulation show an increase to 8,491 m^3/ha for the years 2021-2050 and 9,726 m^3/ha for 2071-2100. In addition, it is predicted that an increased area will be irrigated (McCartney and Menker Girma 2012).

3.4.1 Koga Large scale irrigation scheme

The Koga large scale irrigation scheme is a project in the upper Blue Nile catchment that was commissioned in 2010. It counts as one of the latest large-scale irrigation schemes for small holder farmers in Ethiopia (FAO 2018b). Different studies have concluded that water and land resources are suitable for the development of such a large-scale irrigation project (African Development Fund 2004). The quality of the water used for irrigation is generally suitable. PH, EC (salinity), sodium, chloride, calcium, magnesium, potassium, nitrogen, phosphorus, sulphate, iron and manganese are within the acceptable range according to the FAO's irrigation water quality standards. However, there is a relatively high content of boron. (Melesse and Abtew 2016).

According to the data provided by the Ministry of Water and Energy (2012), the soil texture in this area is uniformly clay and the total available water is 160 mm/m^2. In December of 2012, the soil moisture content at field capacity was 46.71%, the permanent wilting point 30.93% and the initial soil moisture was 15.26 mm/m (Birhanu et al. 2015; Haile and Abebaw 2012). In the Koga scheme, the cultivated crops are wheat, barley, bean, maize, cabbage, potato, tomato, onion, shallot, and pepper (Asres 2016).

The area of this catchment is roughly 220 km^2 with a 17 km^2 large reservoir behind the Koga dam. The dam's exact location in geographic coordinates is 11.35°N latitude, 37.14°E longitude, 1900 m above sea level. The reservoir's capacity is around 83.1 million cubic meters (MCM) and is planned to irrigate not more than 7000 ha of land in this scheme (Asres 2016; MacDonald 2004) In this area, soil erosion, deforestation, and poor land use and management are the biggest environmental problems that have been observed (Melesse and Abtew 2016).

The area is characterized by a wide range of slopes and the lack of using advanced techniques. Furrow irrigation is the preferred and recommended method for the distribution of water to the fields (Desta, G., Getaneh, M. and Tsigie 2013). The irrigation system consists of around 1,132.7 km of canals. 19,7 km are lined main canals, 52 km are lined secondary canals, 156 km unlined tertiary canals and 905 km unlined quaternary canals. 11 lined Night Storage Reservoirs can also be found within this system (Asres 2016). The main canal is designed to provide irrigation water 24 h/day during the irrigation period, while the 12 secondary canals are made to supply irrigation to areas for 12 h. The maximum field canal design capacity is 30 l/s. (MacDonald 2004)

The evaluation of irrigation water management practices as well as the analysis of water demand and supply have shown areas for improvement. Overirrigation in early stages of crop development, underirrigation during the period of peak crop water demand and inadequate canal maintenance have led to the overuse of water by roughly 10%. It also shows a lack of technical and agricultural expertise (Asres 2016). Of the 7.000 ha that the scheme was designed to irrigate, the actual irrigated area was 5144.36 ha in 2012/13 at its maximum. A mismanagement of the reservoir's water or a flawed design of the scheme appears to be the reason (Birhanu et al. 2015).

3.4.2 Finchaa sugar estates

Finchaa sugar estates is one of the sugarcane cultivators and located in the zone of Horo Guduru Welega in the Oromia Region in Ethiopia. The Estates consist of three separate sub-estate sugar cane farms named West-bank, East-bank, and Nashi. Nashie farm is the latest expansion of Finchaa sugar estate. Proper irrigation of sugarcane crop during the dry period (October-May) is crucial for successful crop production. Both the East and West Bank are irrigated by water from the Finchaa River. Separate canals provide the areas with water for sprinkler irrigation (Terefe and Sing 2019).

East-bank sugar estate is located between 9°30’ to 10°00’ N latitude and 37°15’ to 37°30’ E longitude. It is separated from the West Bank estate by the gorge of Finchaa River. The area is at an altitude of around 1,350 m on average. Due to the gentle undulated surface with a slope of 0 to 5%, sprinkler irrigation has become the preferred and chosen irrigation system (Terefe and Sing 2019).

East-bank sugar estate is in a warm humid tropical zone with a mean annual maximum air temperature (T_{max}) of 33.2°C, a mean annual minimum air temperature (T_{min}) of 15°C and a mean annual rainfall of 1,276.5 mm. The long year average of daily recorded maximum wind speed is less than 3 km/h, which is low and desirable for sprinkler irrigation. (Terefe and Sing 2019) The soil of Finchaa valley consists mainly of two groups: Reddish Brown (Chromic, Hepallic and Gleyic) with 73% and Black Eutric Vertisols with 27% (Dinka 2016).

East-bank sugar estate’s water acquisition and conveyance system consists of multiple components. Manual regulation of a single radial gate at the headwork regulates the flows into the main canals. Gravity fed as well as pump fed systems distribute water to each field from canal off-takes. Water from these off-takes flows through closed pipes of main lines, sub-mains and laterals to reach the fields. Irrigation water is supplied by 36 m long hoses feed semi-portable dragline sprinklers. (Terefe and Sing 2019; Dinka 2016). The evaluation of Overhead Irrigation system performance at Finchaa, East Bank Sugar Estate by Terefe & Singh has shown similar issues to the Koga irrigation scheme. The lack of technical expertise has led to a poor utilization of the irrigation system, resulting in a large variation of operating pressure. Poor maintenance also led to leakages. All this led to an improper functioning of the distribution system, to water logging problems, and therefore to a non-uniform plant growth (Terefe and Sing 2019).

4 Related Work

In this chapter, previous research on this subject from other scientists not linked to this study, and their results are being reviewed and discussed. The chapter specifically focuses on the previous land suitability evaluations and water demand assessments made in the Blue Nile Basin, the methodical approaches chosen, assumptions made, and results generated by the researchers.

4.1 Land suitability and water demand for agriculture in the Blue Nile Basin

Recently, in 2023, agriculture was overtaken by the service sector as the main contributor of GDP with 36% and 37% respectively (Statista 2024). Nonetheless, since agriculture plays a major role in Ethiopia's working market as it provides jobs for 79% of its inhabitants (World Bank 2021), agricultural profitability, and the useable land is crucial. Approx. 22 of the 55 million ha of Ethiopia's arable land are currently cultivated (Awulachew 2005; Werfring et al. 2004). An obstacle for the determination of any properties like land suitability, agricultural productivity or comparable is that most of the studies performed define their study areas based on administrative districts, which, of course, are not matching with for example watersheds which is more reasonable when it comes to the assessment of land suitability for agriculture which in the end leads to the calculation of water demand for irrigation.

As earlier explained, traditional agriculture in the Blue Nile Basin is rainfed (Seleshi and Camberlin 2006). Other sources indicate that traditional agriculture also includes simple irrigation techniques of surface diversion (Makombe et al. 2007) but since these methods, which have already been applied throughout a long time, are not considered as pivotal for the agricultural demand assessment. Since water was only abstracted from the river system for domestic use in former times, the reduction of the Blue Nile discharge was negligible. Next to surface water, ground water is also used, but in very low volumes compared to surface water, so it is not further considered (Worqlul et al. 2015). With the technical advances making irrigated agriculture possible and with artificial water reservoirs built and to be built on the Blue Nile, the water abstractions from the river are rising. In this section, approaches and results from other researchers on the agricultural water demand in the Blue Nile Basin are presented. A severe obstacle for this kind of review is the differences in the definitions of the study area because only a few studies base their choice on the same parameters as explained in the upcoming sections.

The eight major rivers in Ethiopia bear enough water so that about 3.5 million ha of agricultural land could be irrigated. Currently, only about 150,000 ha are irrigated. (Awulachew 2005; Werfring et al. 2004) About 4% of the 150,000 ha, irrigated land belongs to the private sector (Haileselassie 2000). According to the irrigation development strategy of the Ethiopian government from 2001, about 470,000 ha should have been irrigated by 2016 of which 52% should be large-scale (>3,000 ha) and medium-scale (200-3,000 ha) schemes. The rest of 48% therewith should be small-scale (<200 ha) schemes. (Government of the Republic of Ethiopia 2001) By 2014, already 1,5 million ha had been developed to irrigation agriculture (Worqlul et al. 2015).

(Worqlul et al. 2015) performed a study on the Lake Tana Basin focused on land suitability for surface water irrigation. The results were generated and classified in line with the FAO guidelines for land evaluation (FAO 1976) and in specific for the surface irrigation systems (Walker 1989) resulting in the classes S1 (highly suitable) to S4 (not suitable). The study includes the access to market and river proximity by calculating the distances to the road networks, larger cities, and the perennial rivers respectively via projection of the location of the observed land parcels to a Mercator (UTM) Zone 37N zone. Aside from the location-related suitability, the climate suitability was determined based on the irrigation water requirement, which results from the aggregation of monthly deficits, which are the differences of monthly precipitation and potential evaporation. Small deficits were classified as S1, large deficits accordingly as S4. Additionally, the land-characteristic suitability was also considered slope, soil type, and current land use. The slope was classified into 0-2% (S1), 2-4% (S2), 4-8% (S3) and >8% (S4) (Worqlul et al. 2015) in line with the FAO guideline for Integrated Planning for Sustainable Management of Land Resources (FAO 1999). The soils were classified to the four available suitability groups according to the FAO soil definition guideline (IUSS Working Group WRB 2007). High fertility soils like Luvisols were classified as S1, decent fertility soils like Vertisols, Fluvisols and Cambiosols were classified as S2, low fertility soils like Regosols and Alisols were classified as S3 and the gravely, stony Leptosols are classified as S4. For the suitability of the current land use or land cover, agricultural use was assigned to S1, grass lands to S2, shrub land to S3, and forest area to S4. (Worqlul et al. 2015) The importance of the factors included were generated via pairwise comparison (Saaty 1977). Generally unavailable areas like forest, protection areas, cities, water bodies were excluded from the base dataset. The results show that 61% of the area is suitable for irrigation. From the considered factors, the proximity to the river was the most impacting factor, which is followed by road proximity, slope, soil, precipitation deficit, nearby cities, and the current land use being the least weighting factor. (Worqlul et al. 2015)

A study from Nigussie et al. from 2019 focuses on the assessment of suitable land for surface irrigation in ungauged catchments in the Blue Nile Basin (Nigussie et al. 2019). Other than described in the thesis title, the study was not performed in the whole Blue Nile catchment area but only the district Jabitenan, called Woreda in the local language, which only covers an area of 1,200 km^2 or 6% of the Blue Nile catchment area. It has to be mentioned that the study indicated the size of the study area with 12.000 km^2 in the descriptive part, which is incorrect. Further percentual data given by the authors in the results section confirm this error as these values only make sense with 1,200 km^2. In the Jabitenan district, three gauged and seven ungauged catchments. The data used during the research can be divided in climate data for which daily rainfall, temperature, wind speed, sunshine hours and relative humidity was used, land features for which soil and land use data as well as a 30 m DEM for slope determination was used and the stream discharge of the three gauged catchment for which daily stream flow data was used. The approach implemented was done in three overall steps: Quantification of the Surface water availability during the dry phase from January to May through application of a model using the Soil and Water Assessment Tool called SWAT, developed by (Arnold et al. 1998), secondly, the land suitability assessment for surface irrigation applying an MCDA method in GIS based on topography, soil properties, and proximity to surface water bodies developed by (Aguilar-Manjarrez and Ross 1995) and lastly, the evaluation of the potential area which can be irrigated with surface water resources. For the suitability classification of the factor considered, the system based on four suitability classes from the FAO framework for land evaluation was applied (FAO 1976).

In its intent, the SWAT model combines the evaluation of land management practices, discharge, sediments transport and the nutrient cycle on certain predefined areas labelled as Hydrologic Response Units (HRU) (Nigussie et al. 2019). This results in discharge and water balance predictions using interpolation for the observed study area. The slope was classified into 0-2% (S1), 2-4% (S2), 4-8% (S3) and >8% (S4) as in the study from Worqlul described above. The soils were classified according to the world reference base for soil resources from the FAO, which (FAO 2014) which represents progress related to sources used in previous studies. Eutric Cambisols and Haplic Nitisols were classified as S1, Eutric Fluvisols, Haplic Alisols, Eutric Leptosols and Eutric Vertisols were classified as S2, while none of the present soils were classified as S3. The S4 or not suitable class was assigned to Dystric Leptosols, Lithic Leptosols and urban areas. For the river proximity, a simple layer with increasing distances to the closest river was created. The land Use suitability was included by applying the FAO framework for land evaluation (FAO 1976). The land uses were divided into suitable areas such as dominantly and moderately cultivated areas as well as state farms and unsuitable areas like open woodlands or urban areas. The pairwise comparison of the factors resulted in slope being by far the most affecting factor with 0.39 followed by soil drainage properties, soil depth, soil texture, land use and the least affecting factor being the river proximity with a weight of 0.04. About 5% of the observed districts were labelled as not suitable because of the slope being above 8%. Only 4% of the study area needed to be excluded due to land use constraints. Only 9% of the study area needed to be classified as unsuitable due to the soil properties. Including the remaining factors, a total of 456 km^2 (38%) was estimated as suitable for irrigated agriculture in the study area. Considering the water requirement of the typically cultivated plants and the available water through the adjacent streams, the area even was reduced to 38.9 km^2 (3,24%) since the discharge of the nearby river would not be high enough during the observed dry season to irrigate a larger area. (Nigussie et al. 2019) From the Ethiopian perspective, this underlines the main assumption of this study that is it not the suitable land that is lacking for higher agricultural productivity but the lacking water resources and the necessity to store the water from the precipitation intensive months in late summer to be able to irrigate a larger area for a longer period of time.

In 2008, Tsehayu published a baseline survey of irrigated and rainfed agriculture in the Blue Nile Basin in the framework of the project “Information Products for Nile Basin Water Resources Management” supported by the FAO (Tsehayu 2008). The study aims to establish a link between agriculture and water and to point out the potential to increase agricultural productivity for rainfed and irrigated agriculture. The study follows a different approach than others to define the study area not by administrative districts (Worqlul et al. 2015; Nigussie et al. 2019), or catchment areas belonging to a specific pour point, like it was done for this study. A pour point is a specific selected point in a river system which marks the discharge point of the whole river network linked to this point. (Tsehayu 2008) The survey, however, defines the study area as the “Ethiopian part of Nile”, which are all catchment areas which at different points merge into the Nile River system. Some areas, for example, drain in the Blue Nile system, some in the Black Nile system and some in the White Nile system. Because of that, the results gained from this study needed to be handled carefully as they refer to a very large area. Compared to all other considered studies. Due to the rugged terrain, especially in the central and eastern parts of the Blue Nile basin, the survey points out that the agricultural potential lies specifically in the further development of small-scale farms. Low productivity, however, is not only existing due to small yields but also through lacking proper infrastructure, which makes the access to the market more difficult and lowers the revenue of sold crops. The existing potential for the actual Blue Nile river as it is considered in this thesis demarks 7,190.88 km^2 whilst the whole catchment area is 199,812 km^2 in size. (Tsehayu 2008)

A publication from Block and Strzepek from 2010 focuses on the economic analysis of Large-Scale development in the Blue Nile Basin, including transient condition, climate variability and climate change (Block and Strzepek 2010). The authors claim to fill the gaps from previous studies on economic benefits of the planned dam cascade along the Blue Nile (going downstream Karadobi, Beko Abo, Mendaya, GERD) and the resulting available water for irrigation because the influence of less available water during filling phases of the reservoirs and climate change were not included. Leaving these factors out would lead to an overestimation of the potentially available water for irrigation and hence the revenue from agricultural projects as well. The modelling of the dam cascade system started already in the 1960s and was ongoingly refined with progressing computational progress (Walters et al. 1966; Guariso and Whittington 1987; FAO 2004; Wheeler et al. 2016; Basheer et al. 2018). For the study by Block and Strzepek, an own deterministic optimization model called Investment Model for Planning Ethiopian Nile Development (IMPEND) was created to include factors affecting future investment decisions like the effects of transient filling stages on the downstream flow condition and discharges, and different climatic scenarios (Block and Strzepek 2010). The two overserved scenario are “no stagger” meaning that the four dams are simultaneously built over a period of seven year and they are completely filled from the beginning on, which marks the optimal scenario and a second one called “stagger” in which den dams are built in subsequently in seven-year period and their reservoirs being empty from the beginning on. Additionally, two flow policies towards the downstream countries were assumed. The first being the 5% policy reflecting the situation that 5% of the annual flow of the Blue Nile will be retained in the dam cascade. The second being the 50% policy reflects the situation that any discharges above the median discharges based on the historical record will be retained in the dam cascade. (Block and Strzepek 2010) The results showed that in the staggered 50% scenario, the discharge towards Sudan will decrease by 2.7 BCM or 6%, while in the not staggered 50% scenario it will decrease by 1.6 BCM or 3.5%. Results for the 5% policy were not provided in the study. The results also showed that through storing the water in the dam cascade in Ethiopia rather than in the reservoirs downstream in Sudan and Ethiopia, evaporation losses can be reduced by approx. 4-5 BCM as the losses are estimated to be around 4-5 BCM at Lake Nasser in Egypt and only 150 MCM in Ethiopia. (Block and Strzepek 2010) Even though the study gives insight into the effects of the dam cascade being built, it does not reflect future development of using the water store in the cascade as irrigation water and deducting it from the downstream discharge.

In 2016, Yalew et al. did a land suitability analysis in the Abbay basin using remote sensing, GIS and AHP techniques (Yalew et al. 2016). Hence, at least from the premise it is comparable to this study. The factors considered for the analysis are the soil type, soil depth, soil water content, soil stoniness, slope, elevation, proximity to roads and urban areas and surface water sources in line with commonly applied guidelines like ALES (Rossiter 1990). The overall classification in suitability classes has been done in four classes/scores. Areas with a factor of class/score 4 reflect highly suitable areas, 3 reflects moderately suitable areas, 2 reflects marginally suitable areas, and 1 reflects unsuitable areas (Yalew et al. 2016). The latter in addition are marked as permanently unsuitable. Areas like forests, preservation areas and water bodies were generally excluded from the assessment and marked as permanently unsuitable as well.

Table 7: Ranges for suitability classes/score of the considered criteria

Factors	Unit	Suitability score			
		4	3	2	1
Slope	°	0-7	7-15	15-25	>25
Soil depth	cm	>90	50-90	20-50	0-20
Soil stoniness	%	0-3	3-15	15-50	>50
Soil type	-	NS, LS, CS, PS	VS, AS	HS, LpS	-
Soil water content	%	90-100	70-90	30-70	<30
Distance to urban areas	km	0-5	5-10	10-30	>30
Distance to road network	km	0-3	3-6	6-10	>10
Distance to water	km	0-1.5	1.5-3	3-5	>5

For the slope, the classes were assigned in descending order for 0-7°, 7-15°, 15-25° and >25°. For the elevation, it was simply assumed that all areas lower than 3,700 m.a.s.l. are suitable as this marks the border to the frost-alpine, agro-ecological zone high Wurich. The soil depth was classified in descending order in the ranges >90 cm, 50-90 cm, 20-50 cm and >20 cm. The soil water content was classified in descending order in the ranges 90-100%, 70-90%, 30-70% and <30%. The soil type was classified in descending order as nitisols (NS), luvisols (LS), cambisols (CS) and phaeozems (PS) for class 4, vertisols (VS) and alisols (AS) for class 3, histosols (HS) and liptosols (LpS) for class 2. None of the soils occurring in the study area have been classified in the lowest class as permanently unsuitable. The soil stoniness was classified in descending order in the ranges <3%, 3-15%, 15-50% and >50% stones. The distance to urban areas was classified in descending order in the ranges <5 km, 5-10 km, 10-30 km and >30 km. The distance to the road network was classified in descending order in the ranges <3 km, 3-6 km, 6-10 km and >10 km. The distance to surface water sources was classified in descending order in the ranges <1.5 km, 1.5-3 km, 3-5 km and >5 km. All of the datasets were processed to be available as raster data. The comparability was already given from the beginning, as the author chose to classify all factors in 4 numerical classes with corresponding scores. The weights have been assigned to each of the factors through performing the AHP method. This resulted in 1.9% for the elevation, 2.6% for the distance to surface water sources, 3.7% for the soil type, 5.3% for the distance to urban areas, 7.6% for the distance to the road network, 10.9% for soil depth, 15.4% for the stoniness of the soil, 21.8% for the slope angle and 30.7% for the soil water content. The results showed that 28.6% is highly suitable, 48.9% is moderately suitable, 6.2% is marginally suitable and 6% is unsuitable. The remaining 10.3% are unavailable due to previous made assumptions that, for example, areas covered with forests are not available for agricultural development. (Yalew et al. 2016)

Kassie et al. did a land suitability evaluation with focus on surface irrigation in the Blue Nile Basin in 2022 (Kassie et al. 2022). Both surface and ground water sources were considered for this study in separate scenarios. The evaluation was done through a MCDA method in which includes the slope of the observed area, the distances to rivers, urban areas and roads, the population, the soil capability index consisting out of soil depth, texture and drainage properties, the land use, the existing shallow groundwater resources and the climate in terms of precipitation deficit. Shallow groundwater resources have been defined as aquifers in less than 25 m depth. After reclassification to unify the datasets, the factors were weighted through the pairwise ranking method and a weighted overlay was performed afterwards. Then, a constraint map or exclusion criteria map was created and the respective area removed from the results. As exclusion criteria were defined as water bodies, wetlands, urban and protected areas. The validation of the results was done by comparing the results with available data from the shallow groundwater wells and also information on currently existing irrigation schemes or farms using surface water resources. The authors followed the general framework for land suitability classification for irrigation from the FAO (FAO 1976) with using five suitability classes as displayed in Table 8.

Table 8: Suitability classes as applied in (Kassie et al. 2022)

Class	Name	Land description
S1	Highly suitable	Land without significant limit; this land is the best possible and does not reduce productivity or required increased inputs
S2	Moderately suitable	Land that is suitable but has a limitation that either reduces productivity or requires an increase of inputs to sustain productivity compared with S1
S3	Marginally suitable	Land with limitations so severe that benefits are reduced and/or the input required to sustain production needs to be increased so that this cost is only marginally justified
S4 (N1)	Currently not suitable	Land having limitations that may be surmountable in time but which cannot be corrected with existing knowledge at a currently acceptable cost
S5 (N2)	Permanently not suitable	Land having limitations that appear as severe as to preclude any possibilities of successful sustained use of the land for a given land use

The slope was classified differently as in previously discussed studies a 0-2% is classified as S1, as in other studies, but den diverting as 2-8% are being classified as S2, 8-12% as S4, 12-30% as S4 (N1) and >30% as S5 (N2). For the suitability of the soil, the soil capability index was used which is calculated as follows:

$$SCI = A \times \left(\frac{B}{100}\right) \times \left(\frac{C}{100}\right) \quad 158$$

While A represents the soil texture rating, B represents the soil depth rating and C represents the soil drainage class rating. Here again a classification in four classes but with slightly different termini, namely highly suitable (>80%), moderately suitable (60-80%), marginally suitable (45-60%), less suitable (30-45%) and currently not suitable (<30%) was done accordingly with (Teka et al. 2010). It should be noted, that (Kassie et al. 2022) introduced a 5% gap between marginally suitable and less suitable stating the range for marginally suitable is 45-60% and the range for less suitable is 30-40% which seems to be an error in adapting the approach from the original source. The soil texture rating was derived by assessing the water-holding capacity of the soils and classifying them in the study area in four groups. Soils consisting of silt, silt loam, and silty clay loam were classified as highly suitable, silty clay and clay as moderately suitable, sandy clay loam as marginally suitable, and sand as not suitable. (Kassie et al. 2022) Soil depth classification in four classes was done in line with FAO's framework for land evaluation (FAO 1976) i.e. areas with soil depth >1 m were considered as highly suitable, 0.8-1 m as moderately suitable, 0.5-0.8 m as marginally suitable and not suitable <0.5 m. The soil drainage rating in four classes was derived from the level of aeration of the soils, which is linked to the soil depth. Accordingly, the drainage level is reflected by the soil depth, meaning that soil depth >1 m implies well-drained to moderately drained soil, 0.8-1 m implies imperfectly drained soil, 0.5-0.8 m implies poorly drained soil and very poorly drained soil at soil depths <0.5 m. (Kassie et al. 2022) The better drained the soils, the better is the aeration and associated with this, optimal plant growth. The classes range accordingly from highly suitable to currently not suitable. Regarding the land use cover, land already in agricultural use was classified as highly suitable, grasslands moderately suitable, shrub and bare land as marginally suitable, rock land, woodland, bamboo, forest and plantations as currently not suitable and water bodies, urban areas and wetland as permanently not suitable. The distances to rivers, urban areas and roads, as well as the population density, are being considered as indicators for good access to the markets to sell the crops. Short distances also imply short conveyance ways for the irrigation water. The distances to the road and river networks and urban centres were calculated using the Euclidean distance method and classified with the equal interval ranging technique according to (Teshome and Halefom 2020). Because of the high variability in the population density observed by the authors, the geometric interval ranging technique according to (Huan et al. 2012) was applied to classify the observed land. The precipitation deficit reflecting the necessity for additional water application on the field depending on the cultivated crops is considered as well. Simply described, the precipitation deficit is calculated by subtracting the evapotranspiration and the water demand of the cultivated crops from the precipitation. If the result is positive, no additional irrigation is needed. If it is negative, water needs to be added to successful plant growth. To determine the reference evapotranspiration ET_o applying the Penman-Monteith method (García-Gutiérrez et al. 2021), the ten-year monthly average for the necessary climate data was taken from 58 meteorological stations from the Ethiopian Meteorological Agency. Data gaps were filled through the arithmetic average technique and normal mean ratio method (Kassie et al. 2022). The groundwater depth was classified into very shallow for aquifers in less than 7m depth, shallow if they are 7-25 m deep and the remaining aquifers in 25-50 m depth. The salinity was assessed considering the concentration in total dissolved solids (TDS) based on (Singh and Singh 2008). Lastly, the irrigation water demand was calculated using the following equation:

$$NIR = 1.6 \times K_c \times ET_O \times ER \qquad 159$$

Where NIR is the net irrigation requirement in mm, K_c is a dimensionless crop coefficient, ET_o is the aforementioned reference evapotranspiration and ER is the effective precipitation in mm. The factor 1.6 pays tribute to the inefficiency of irrigation techniques like conveyance losses due to evaporation or seepage and land losses for preparation or leaching (Yimam et al. 2021). The weights have been determined once for each base scenario, depending on whether the irrigation water should be withdrawn from aquifers or surface resources, both through pairwise comparison. For the latter, comparison resulted in 4% for the current land use, 6% for the precipitation deficit, 8% for the proximity to the road network, 9% for the proximity to urban centres, 10% for the population density, 18% for the soil capability index, 20% to the slope and 26% to the river proximity. For the groundwater scenario 4% were determine for the current land use, 6% for the proximity to the road network, 7% each for the precipitation deficit and the proximity to urban centres, 9% for the population density, 18% for the soil capability index, 20% for the slope and 30% groundwater depth 30 m. The results showed that a total of 19,165 km^2 or 9.59% of the area in the Blue Nile Basin is suitable for irrigated agriculture with surface water as a source. For groundwater, the area is approx. half the size with 10,364 km^2 or 5.19%. The validation of the land suitability assessment was done through comparison of the results with existing irrigation schemes. It showed overlapping of 88%-100% for different observed subbasins of the Blue Nile Basin with the exception of two (30% and 40%). (Kassie et al. 2022)

During a study published in 2019 on the land cover change in the Blue Nile area, Cherinet et al. found that approx. 5,878.42 km^2 or 29,42% of the area is cultivated land (Cherinet et al. 2019).

According to the Abbay Atlas, about 34% of the Blue Nile Basin is currently under rainfed agriculture. 8,155.81 km^2 or 4.01% of the basin is potential irrigable land of which 458.56 km^2 would be small-scale farming, 1,303.95 km^2 would be medium-scale farming and 6,393.30 km^2 would be large-scale farming. (Geremew Y. 2020)

Birhanu published a review in 2023 on surface water potential and irrigation development in Ethiopia (Birhanu 2023). The review indicates that 11% or 21,186 km^2 of the Blue Nile Basin can be irrigated, not mentioning the exact source of these numbers.

In the framework of a land cover change detection using remote sensing methods in 2022, Tikuye et al. found out that approx. 123,175 km^2 or 61.65% of the Blue Nile Basin is cropland. (Tikuye et al. 2023)

In 2024, a study was done by Bashe et al. on the economic productivity of irrigation water in the Blue Nile Basin (Bashe et al. 2024). Using a combination of remote sensing and gathered information from responsible administrative offices, the authors figured out an area of 751,95 km^2 or 0,37% of the Blue Nile Basin is under irrigation during the time of the study, which is less than 1% of the area that could potentially be irrigated. About 99.861,61 km^2 were indicated as rainfed croplands. (Bashe et al. 2024)

The literature review on related work showed that as many factors that are to be considered in the process of estimating the area suitable for agriculture in general or irrigated agriculture in particular, yield many different results. On one hand, literature results are limited due to diverting study areas as many of the public information is limited to administrative districts which are not matching with climatic or hydrologic zones. The remaining data with the same study area like (Yalew et al. 2016) or (Kassie et al. 2022) confirm the overall approach to the topic, but their results are still dependent on the subjectivity every study has in specific, when it comes to the consideration which factor to include in the evaluation and what weights to assign to the factors. Due to that, it is hardly possible to validate the results against outcomes of other studies, especially when it comes to future estimation of developments.

5 Preliminary work

Before figuring out the approach finally followed to generate the results described in a later section, several other approaches have been determined and tested to generate the first trend-setting results to get a rough impression of the results to be expected later on. Throughout the process, the approaches started simple, became more complex as the first ones were based on the exclusion of areas step by step and the final ones included software-based automated Multi Criteria Analysis.

The first section of this chapter describes the first approach undertaken to get an impression of the overall land suitability on the study area. For doing so, only basic and publicly available data like elevation and climate data were used and certain areas were excluded in a generalized manner by cutting the respective areas from the study area in GIS.

The second section of this chapter describes a multi-staged approach developed using model creating tools in GIS to introduce a weighted effect of several factors. For this approach, the plants to be cultivated were considered as well to add plausibility and detail to the generated results for land suitability.

The third section of this chapter describes the final approach applied to generate the first results of this research related to land suitability evaluation for agricultural cultivation of selected crops. The approach includes the application of the software LSE from Ngyuen et al. (Nguyen et al. 2020) described under section 2.2.

5.1 Approach 1: GIS-based multi-staged exclusion model

At the beginning of the research, it was necessary to get an overview of the scale of available land for any kind of use, and specifically for agricultural use, so that any further change in the approach and also the results found in literature could be compared to these. Several small-scale case studies have been carried out which will be further described.

For the first try-out, it was assumed that all areas in the Blue Nile catchment area are suited for agricultural cultivation of plants and that the only limitations to that are the distance to the river and its major tributaries as well as a certain height above the river level. Both assumptions are based on costs for pumping, which would exceed the values that could be assumed as economic. The two parameters were set to 100 km horizontal and 400 m vertical distance to the water bodies. The 100 km distance assumption already showed that the whole catchment area would be suitable for agriculture. This on the one hand gave valuable insights, that the distance to the water bodies is negligible, but on the other hand, no process in limiting the agricultural area could be achieved with this factor. Only having the height left as limiting factor led to unrealistic high results of 149.818 km^2 or approx. 75% of the Blue Nile Basin area being suitable for agriculture, so that a specification of the approach was necessary (see Figure 15).

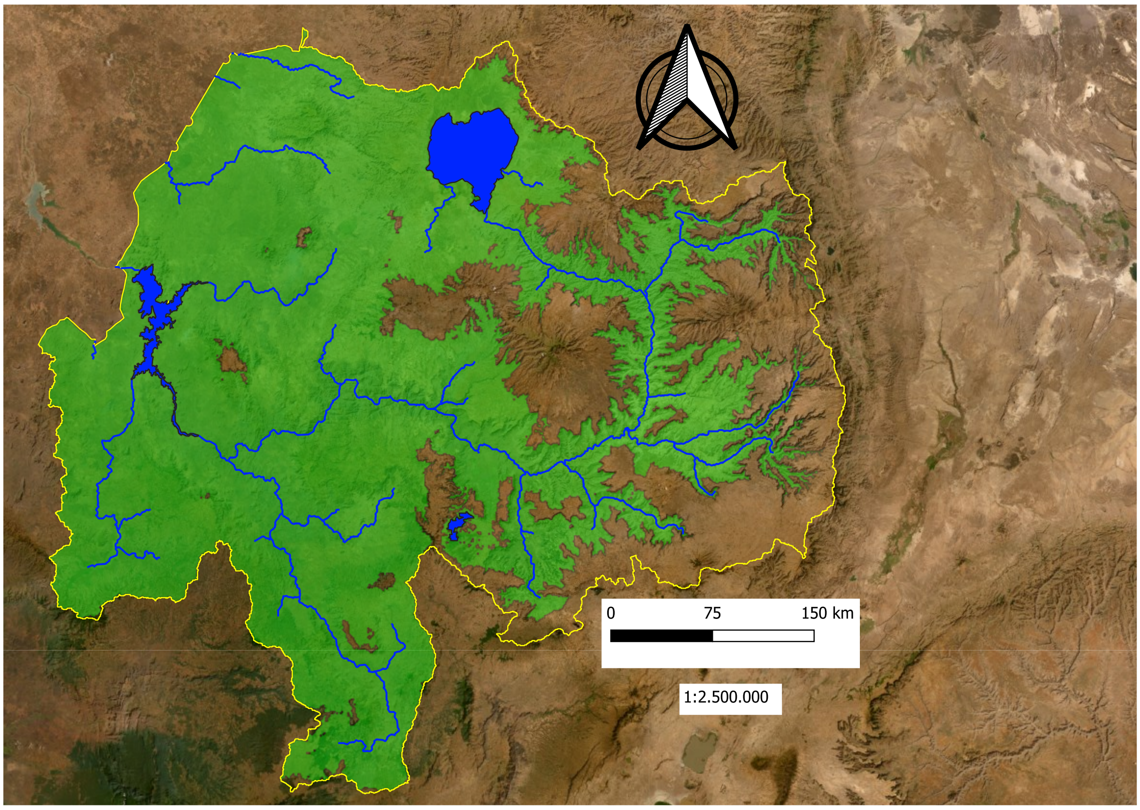

Figure 15: Area indicated as suitable for agriculture after the 1st approach

The next step was to refine the results from the first try out. To do so, more factors like land cover, soil fertility, precipitation deficit, streets, and population density were introduced. The soil fertility in this approach is a combined factor influenced by the content of the soil in organic carbon, its pH values, Cation Exchange Capacity, Base saturation and exchangeable Sodium salts. The range of the factors that allow agriculture in general is listed in Table 9.

Table 9: Suitable value ranges for the considered factors (FAO 2023a)

Factor	Optimal range
Total organic carbon	> 0.6%
pH	5.5 – 8.5
Cation Exchange Capacity	> 10 cmol/kg
Base saturation	50 – 80 %
Exchangeable Sodium salts	< 15 %

To combine the additional factors, their specific weights were determined using the AHP method. The AHP matrix is shown in Table 10, which was implemented in the weighted overlay tool in the GIS software ArcMap.

Table 10: Pairwise weighting matrix

Factor	Land cover	Soil fertility	Prec. deficit	Streets	Pop. density	Distance	Eigenvector	Weights
Land cover	1	3	4	7	8	5	3.2	37.9
Soil fertility	1/3	1	4	7	6	5	2.2	26.6
Prec. Deficit	1/3	¼	1	6	7	5	1.5	17.9
Streets	1/7	1/7	1/6	1	½	1/3	0.3	4.1
Pop. density	1/8	1/6	1/7	2	1	1/3	0.4	4.7
Distance	1/5	1/5	1/5	5	3	1	0.7	8.8
								100.0

This approach gave a more detailed impression on the land suitability in the region. However, apart from the already excluded areas due to distance or height, no other areas could be excluded. The results only provided information that certain areas are less suitable than others, but generally not unsuited. This led to the necessity to develop a more comprehensive approach with strict limitations for the acceptable values as it was done in the second approach, which is explained in the upcoming section.

5.2 Approach 2: Automated Land Suitability Evaluation

5.2.1 Considered Parameters

In another approach, an automated process using GIS software was elaborated. The idea was to create a model in GIS, which needs only the normalized input data for the evaluation to determine agricultural land suitability. The parameters considered for this approach were precipitation, temperature, soil organic carbon, soil depth, slope, soil pH-value, soil texture, and the land cover class according to the FAO. The selection of the parameters was based on FAO's Framework for Land Evaluation. In addition, parameters like pH value have been included as they are considered as important parameters in relevant literature like (Sys et al. 1991). The selected parameters, their displayed units and data sources are listed in Table 11.

Table 11: Parameters used for LSE

Parameter	Unit	Data source
Precipitation	mm	(Worldclim 2022b)
Temperature	°C	(Worldclim 2022b)
Soil Organic Carbon	% weight	(Fischer et al. 2008)
Soil Depth	cm	(Fischer et al. 2008)
Slope	-	(Worldclim 2022a)
Soil pH-Value	-	(Fischer et al. 2008)
Soil Texture	-	(Fischer et al. 2008)
Land cover		(FAO 2003)

The existing raster data had a resolution of 30 min, which approx. equals 1 km^2 cell size. (Worldclim 2022a) The spatial extent of the data was limited to the study area by extraction as most of them cover Earth's complete surface.

The data that had to be processed to fit the model is described below. The thematic maps for all parameters are then presented. Data that had to be processed additionally are slope, land cover, soil organic carbon, soil depth, pH, and soil texture. The slope was calculated from elevation data. This was done using the Spatial Analyst tool 'Slope' in ArcMap. It determines the slope or gradient from each cell of a raster (ESRI 2016c). The land cover was aggregated into 16 different land cover classes by summarizing or assigning polygons according to their land cover classification. The Land Cover Classification System (LCCS) is an FAO concept that assigns a classifier in the form of numbers and letters to each land cover class. In this way, land cover types can be systematically identified. (Gregorio and Jansen 2000) The resulting land cover classes for this study are: Shrubland, woodland, herbaceous, cultivated land, natural water bodies, open shrubs, grassland, consolidated bare land, tree crops, artificial water bodies, unconsolidated bare land, mixed class, forest, uncultivated land, thicket and closed shrubs. The individual land cover types, which are summarized into 16 classes, can be obtained from the (FAO 2003) download folder for land cover data. After summarizing the land cover classes, the polygon data were converted into a raster dataset. The soil data of organic carbon, depth, pH and texture were taken from the FAO Harmonized World Soil Database (HWSD). With the exception of soil depth, the data refer to the topsoil, which is defined as 0-30 cm below the surface.

5.2.2 Weighting of Parameters

The parameters were weighted following the Analytical Hierarchy Process described in chapter 2.1.1.

For calculating the relative weights, the ArcGIS extension ‘extAhp20’ (ESRI 2017) was used. Subsequently, the toolbox ‘AHP’ (Habboub 2024) was used to validate the calculation. The Input parameters for the matrix are all parameters as described in chapter 5.2.1. The final matrix is shown in Table 12. The scale after (Malczewski 1999) is used to set the preference for the factors making the values range from one to nine. The specific preference factor to compare each parameter against each other (pairwise comparison) was derived from literature review. The literature used is: (Fekadu and Negese 2020; Nigussie et al. 2019; Feizizadeh and Blaschke 2013; Chen et al. 2010; AL-Taani et al. 2021; Matori and Chandio 2011). If no values were found, it is assumed that two parameters have an equal importance and a value of one is assigned. During this study, this was applied for the pairwise comparison of temperature and land cover, land cover and soil organic carbon, land cover and pH-value, land cover and precipitation. The final pairwise comparison matrix is shown in Table 12 and reads as follows. If, for example, the slope layer on the x-axis and the temperature layer on the y-axis are taken, the preference factor is two. This means the slope has an equal to moderate importance over temperature. After integration of the values from literature review, an iterative adjustment was performed to receive a consistency ratio below 0.1. The result of the AHP calculation that was done with the AHP toolbox is shown in Table 13. The final consistency ratio of the matrix is 0.095781. Hence, resulting weights can be used for further analysis. Table 14 shows the final weight for each parameter or layer, respectively. A comparison between the final weights from the extAhp20 calculation and from the toolbox AHP was made. The last column in Table 14 shows which weights were taken for the further modelling steps. The resulting weights are necessary to apply the tool ‘Weighted Overlay’ in ArcGIS. The AHP extension and toolbox, however, are not part of the model workflow in ArcMap Model Builder. Still, the AHP must be implemented before running the model since the weights are required as parameters for the 'Weighted Overlay' tool as mentioned above.

Table 12: Final Pairwise Comparison Matrix for Analytical Hierarchy Process

Layer	Slope	Temp	Depth	Text	Land cover	Org. carb	pH	Precipitation
Slope	1	2	2	0.5	7	2	0.25	0.5
Temp	0.5	1	0.5	0.333	1	2	0.25	0.5
Depth	0.5	2	1	0.333	3	1	0.5	0.5
Text	2	3	3	1	3	3	1	2
Land cover	0.143	1	0.333	0.333	1	1	1	1
Org. carb	0.5	0.5	1	0.333	1	1	0.25	0.5
pH	4	4	2	1	1	4	1	2
Precipitation	2	2	2	0.5	1	2	0.5	1

Table 13: Result of Analytical Hierarchy Process

Layer	Weight	Consistency Index (CI)	Average Consistency Ratio (RI)	Consistency Ratio (CR)
Slope	0.142056	0.135051	1.41	0.095781
Temp	0.065788	0.135051	1.41	0.095781
Depth	0.09179	0.135051	1.41	0.095781
Text	0.210066	0.135051	1.41	0.095781
Land cover	0.080	0.135051	1.41	0.095781
Org. carb	0.059225	0.135051	1.41	0.095781
pH	0.22498	0.135051	1.41	0.095781
Precipitation	0.126526	0.135051	1.41	0.095781

Table 14: Comparison of Weights from AHP and Final Input weights for Weighted Overlay Tool

Layer	Weights extAhp20	AHP toolbox	Weights for Weighted Overlay Tool
Slope	14.846	12.2056	15
Temp	6.324	6.5788	6
Soil Depth	9.123	9.179	9
Soil Texture	20.742	21.0066	21
Landcover	7.528	7.9568	8
Soil org. carb	5.833	5.9225	6
Soil pH	22.708	22.498	23
Precipitation	12.806	12.6526	12
Sum	100	99.9999	100

5.2.3 Suitability Classification

To classify the results in different ranges, the FAO Framework for land evaluation (FAO 1976) was consulted. A detailed description of the suitability classes was made in section 2.2. In general, the suitable areas for this approach are subdivided into the classes S1, S2, and S3, while S1 being the most suitable areas. For non-suitable areas N, no further subdivision was made. Since only integer numbers can be used for calculation in ArcMap, the values 1 for S1, 2 for S2, 3 for S3 and 4 for N were assigned. To immediately exclude areas for which one parameter ranges in the non-suited class, limiting factors were set. A factor is assumed to be limiting, if its attributes appear too unfitted as to preclude any possibilities of successful use of irrigated agriculture (FAO 1976). If, for example, all parameters indicate best suitability for agriculture, but the area is covered by water (e.g. rivers, lakes), agricultural development in these areas is impossible. For the example of land cover, there is no distinction made between the different suitability classes, but only if agricultural development is possible or not. Accordingly, either S1 or N was assigned to the 16 land covers included in the dataset, which was used. The assignment is displayed in Table 15.

Table 15: Land cover Attributes and their assigned Suitability Class

Land cover	Suitability class	Justification if Not Suitable
Shrubland	S1	-
Woodland	N	Continuous trees/tree forest)
Herbaceous Crops	S1	-
Built Up Areas	N	
Natural Waterbodies	N	
Open Shrubs	S1	-
Grasslands	S1	-
Consolidated Bare Areas	N	Bare rocks (FAO 2003)
Tree Crops	S1	
Artificial Waterbodies	N	-
Unconsolidated Bare Areas	S1	
Mixed Class	S1	
Forest	N	
Non Built Up Areas	N	
Thicket	S1	
Closed Shrubs	S1	

5.2.4 Design of the Model for Land Suitability Evaluation in ArcMap

The model to be described in this section was built using the model builder tool in ArcMap. The model builder tool allows to visualize abstract processes step-by-step. Despite the model being the same for all modeling for the different crops in this approach, the model itself remained the same and only the input parameters changed. The result of the model always is a suitability layer indicating whether a specific area is suitable for agriculture or not. The schematic structure of the model is displayed in Figure 16.

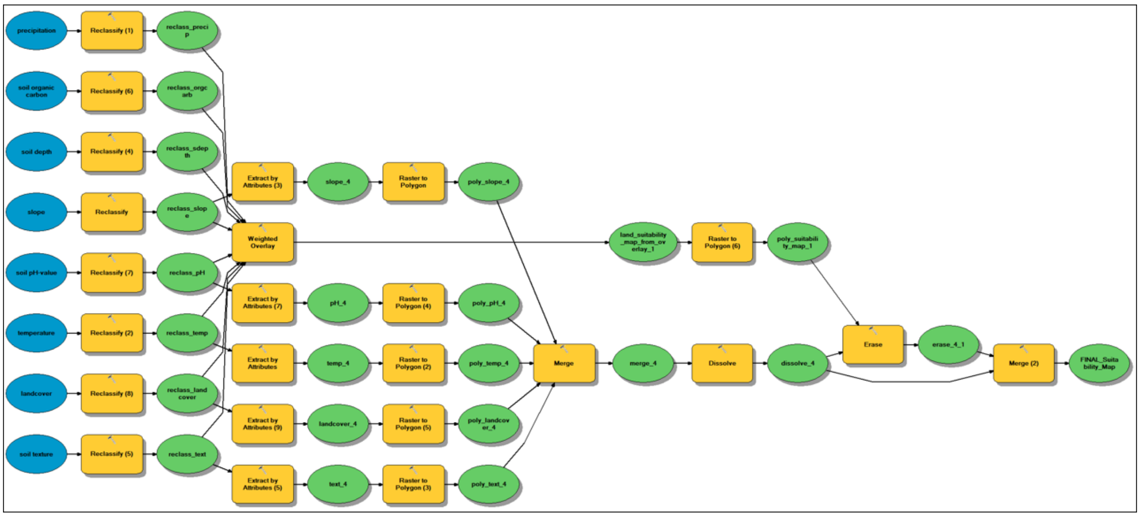

Figure 16: Model Chain of the tested Land Suitability Model

The blue circles represent the input parameters given into the model. Following those in the second stage are processing tools in the yellow squares with rounded corners. In this case, the tool is the "reclassify" tool. This is done to unify the shapes and categorization of the data sets of different origin, and to introduce the suitability classes to the respective attribute tables and assigned values ranges of the parameters to the classes. Otherwise, they possibly could not be combined in the model. The resulting reclassified datasets represented by the green ellipses are further processed in two parallel ways. First, specific limiting values are determined and extracted from the available area. For example, if the land cover is barren rock, it is not possible to cultivate plants in this area. Due to that, this area is excluded from the area suitable for agriculture. Once the exclusion area has been determined and the remaining suited areas have been extracted from the input datasets, so that only the not-suited areas remain. These are then converted into polygons, so that they can be combined using the merge tool. Afterwards, the remaining borders from the input data are dissolved to obtain consistent indication of suited and unsuited areas. In parallel, the reclassified input datasets are fed into the weighted overlay tool to weight the input datasets to each other. Prior to that, weights were indicated for the datasets which have been derived from an AHP performed before. The scale of values for the overlay tool has been set to one to four in steps of one. The weights are entered in percentage values for each layer (= criterion). The output of the weighted overlay tool is a raster file displaying land suitability under consideration of the weights of the input criteria. To allow further processing, this raster was converted into a shapefile as well. Having now the two shapefiles of the not suited areas due to the limiting factors and the overall suitable area, these two can be combined so that the not suited areas are erased from the suitability shapefile. For visualization purposes, the not suited shapefile is then merged again with the shapefile so that the two areas (suited and not suited) can be kept in one single shapefile.

This approach was very promising due to the modularity of the model itself, which would allow expansion or editing of the process compared to other land suitability evaluation tools like from (Nguyen et al. 2015). Still, this simplicity brings some shallowness in the process as well. Another limitation is that only tools which are part of the ArcMap toolbox can be implemented, and the use of ArcMap itself is an eminent limitation since the software is not free to use. Additionally, the AHP methods have to be performed in advance outside of the model. This, however is the common situation, so it could not be accounted as an actual disadvantage.

6 Case study: Blue Nile

6.1 Data Collection and Preparation

Climate data such as temperature and precipitation were obtained from WorldClim (Worldclim 2022a), a database of high spatial resolution global weather and climate data. The average climate data was available for the years 1970-2000 and a spatial resolution of 30 seconds (~1 km^2) was used. Furthermore, the elevation data was collected in a 30 seconds resolution as well, which was derived from the SRTM elevation data. Using the ArcGIS slope tool, the slope of the study area was calculated based on this elevation data.

Soil data was obtained from the World Reference Base for Soil Resources from the FAO (IUSS Working Group WRB 2007). The data obtained covered salinity of the soil, pH value and textural class, all measured at a soil depth of 5 cm. The salinity of the soil was measured by the Electrical conductivity in dS/m. Additionally, information about the drainage classes as well as the soil depth were collected.

Crop requirements were mainly retrieved from (Sys et al. 1993). However, data on temperature and precipitation wasn't available and other sources had to be used. For sugarcane requirements on temperature and precipitation were retrieved from (Galdos et al. 2009) and (Paiboonsak et al. 2004), for potato from (Kamau et al. 2015) and for wheat from (Fekadu and Negese 2020) and (Girmay et al. 2018). Crop requirements of nitrogen, phosphorus and potassium (NPK) were also taken from different sources to complement the list of requirements. Sugarcane's NPK requirements were obtained from (Paiboonsak et al. 2004), potatoes from (Mandal et al. 2020), wheat's from (Fekadu and Negese 2020) and (Halder 2013), maize's from (Abagyeh et al. 2016) and faba bean's from (Kazemi et al. 2016). Information about the land cover as well as the location of lakes and river basins were collected from the Data Catalog of the World Bank and the location of the rivers was collected from the FAO geonetwork (FAO 2025). The coordinates of existing irrigation schemes were taken from (Awulachew 2007) and the locations of the four dams, GERD, Beko Abo, Mandaya and Karadobi were adopted from (Geressu and Harou 2019). The suitable crops for the region have been identified based on a literature review in order to develop the cropping pattern (Eguavoen 2009; Eguavoen et al. 2012; Awulachew 2009; Hamada 2017; Nigussie et al. 2019; FAO 2020; Valipour et al. 2020; Dawit et al. 2020). Sugar cane, cotton, corn, potato, wheat, and faba beans were chosen to represent the currently most popular crops. The values needed for the land suitability evaluation to categorize the given natural condition of climate and soil are based on literature review and are displayed exemplarily for plant X and sugar cane in Table 17 and Table 18.

6.2 Land Suitability Evaluation

6.2.1 Final approach followed for the evaluation

Commonly applied method to determine the land suitability of specific areas for agriculture, focuses on large-scale output areas. Since the study area in the Blue Nile basin contains inconsistent terrain in terms of many drainage valleys and corresponding slopes, conventional agriculture techniques cannot be applied, which supports the currently developed MSSI system because the development of large-scale irrigation schemes is excluded in most of the area. A detailed examination of the local land properties needs to be carried out. Besides manual methods, software-based tools are widely applied to identify land suitability for agriculture. Both imply a predefined weighting of a set of criteria which could be significant for land suitability. By the time, there is no standardized approach to this topic set nor one universally applied software to evaluate the suitability of available land, as the literature indicates (Elsheikh et al. 2013; Nguyen et al. 2015).

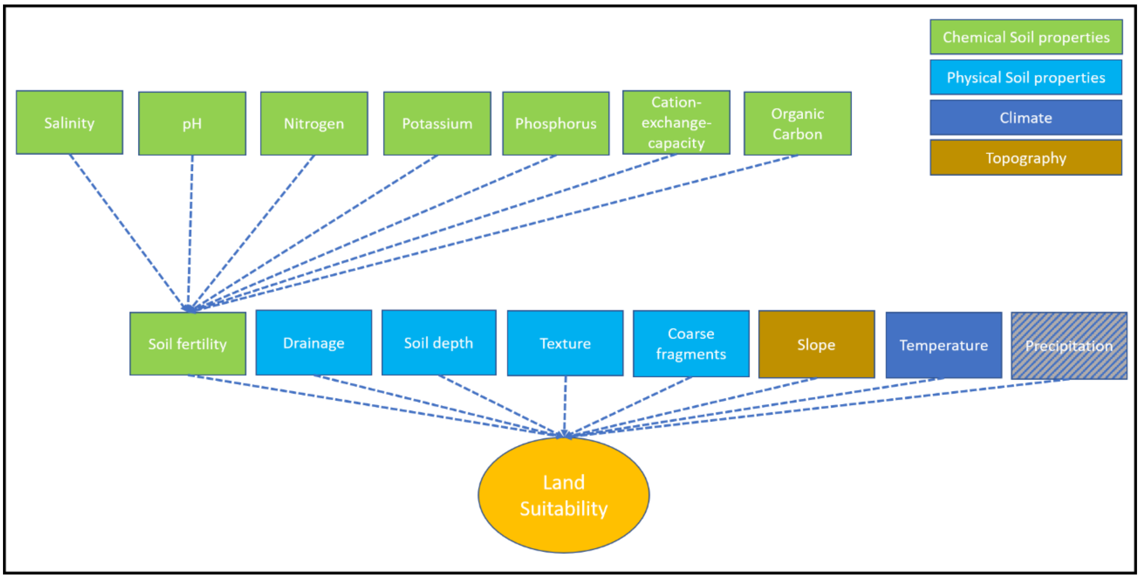

Figure 17: Schematic illustration of the combination process of the criteria for Land Suitability

The main challenge of applying the MCDA is to obtain a sufficient amount of data for the initial developed set of criteria. Therefore, a normalization of the weighting of the specific criteria has been done to compensate for lacking data. The selected criteria are listed in Table 16 and Table 17. A schematic illustration of the combination of the criteria is shown in Figure 17. Sugarcane was chosen as an example here, because it is one of the crops chosen for the LSE where all data is available. It was also important to distinguish between long-term constant criteria like slope or soil texture and other criteria which might be directly influenced by agricultural expansion like available roads and water distribution infrastructure. Since data for the nutrient criteria nitrogen, phosphorus, and Potassium was unavailable, a second stage weighting was developed as displayed in Figure 17. Therefore, the first stage “Soil fertility” is made up of chemical soil parameters as salinity, pH, cation exchange capacity, and the contents of organic carbon, nitrogen, phosphorus, and potassium each with the same weighting. In this case, speaking of seven parameters, each of them makes 14.29% of the overall soil fertility. If not values for all parameters are available, the parameter without values was left out and the weighting was normalised to 100%. For example, when no values for cation exchange capacity are available, the respective 14.29% are equally distributed to the remaining six parameters. Hence, with six parameters, each of them accounts for 16.67% to the overall soil fertility. The applied weighting is based on both literature review of comparable projects and the results of the model's calibration process.

Determining land suitability for different purposes is an omnipresent topic in different fields such as hydrology, geology, agriculture, and regional planning. Accordingly, various approaches have been developed already. Since the objective of this work is to determine the land suitability in the entire Blue Nile basin for agriculture activities, which involves high level of data processing, manual evaluation or stepwise weighting of critical criteria was inappropriate for this study. Two main models have been identified to fulfil the expectations of this research. The automated land evaluation system (ALES), provided by the FAO based on their (FAO 1976) would have been the software of choice since it has already been applied numerous times in different areas around the world for a long time (Rossiter 1990). However, difficulties regarding the compatibility of the software hindered its application as explained in section 2.2.

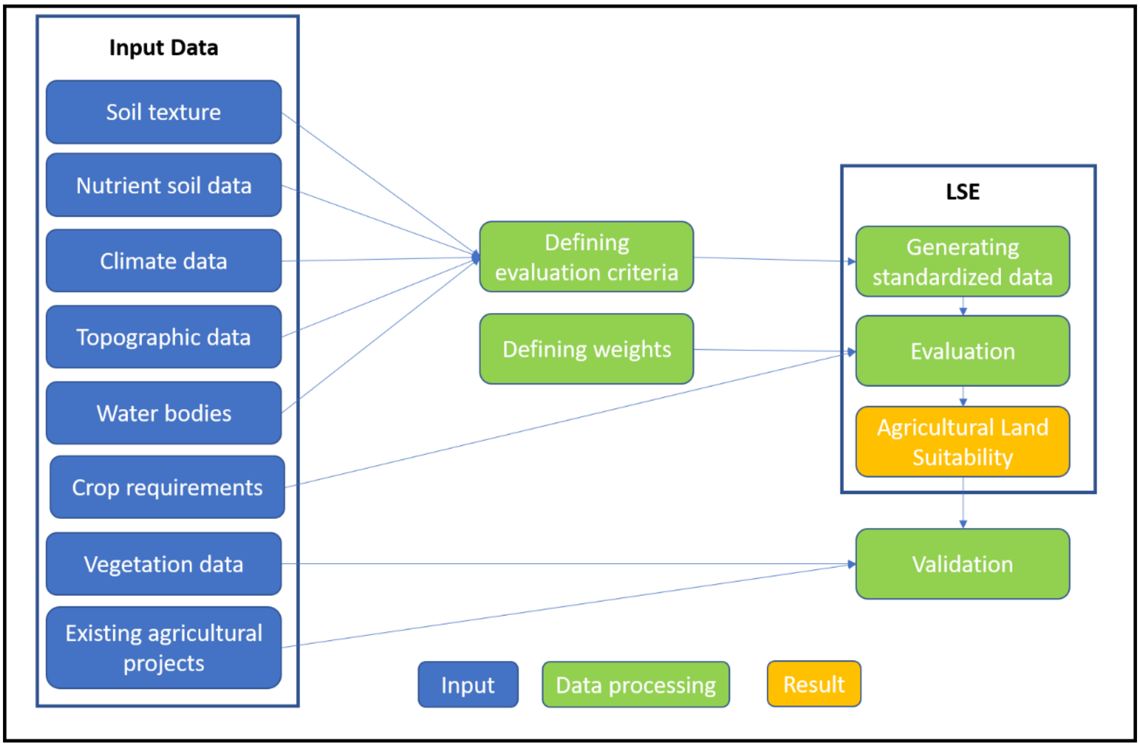

Figure 18: Schematic illustration of the evaluation process

Table 16: Lengths of growing cycle and corresponding water demand for the selected plants

Crop	Length of growing cycle [months]	Water demand per growing cycle [mm]
Cotton (Gossypium hirsutum)	5-7	500-1000
Faba Beans (Vicia faba)	3-4	400-500
Maize (Zea mais)	3-4	300
Potato (Solarnum tuberosum)	3-4	300-700
Sugarcane (Saccharum officinarum)	min. 12	1300
Wheat (Triticum aestivum)	3-4	200

The evaluation of the generated results of previous research with those generated with ALES showed comparable results, whilst being easier to use (Nguyen et al. 2020). Both software follow the basic approach of performing a Multi-criteria Decision analysis (MCDA). The selected criteria have an allocated weighing value which determines their "significance" during the analysis. Another important feature of LSE is to set specific criteria as "limiting factors" meaning that if their associated value does not match the minimal requirements for any suitability class, even if all the other criteria show the best suitability, the whole cell will be considered as not suitable. Having this, some criteria in addition to their weighting can be pointed out as very crucial and unchangeable compared to others. Accordingly, temperature, slope and coarse fragments were set as limiting criteria for the irrigation scenario. For the scenario displaying the status quo, precipitation was considered as a limiting criterion as well. Fourteen criteria have been selected based on the recommendations of Sys et al. (Sys et al. 1993). To determine the land suitability for agriculture and experiences from previous research on the influence of static soil properties such as bulk density, porosity, pore size distribution, and saturated hydraulic conductivity, and coarse fragments. It has to be mentioned that an increasing share of coarse fragments leads to an increase of the remaining static soil properties. (Chow et al. 2007) Hydraulic conductivity plays an influential criterion for plant growth. Cation exchange capacity (CEC) is a measure of negatively charged sites on the surface. The negative charge helps to hold positively charged ions and nutrients such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), and Zinc (Zn). (Kumar et al. 2016) Soil organic carbon is a component of soil organic matter. An adequate supply of organic matter is responsible for a fertile soil. Organic matter acts both directly and indirectly. The processes of decomposition and mineralization affect the provision of plant nutrients directly and the physicochemical properties of the soil indirectly (Campbell 1978).

They can be divided into three groups: Topography and wetness represented by temperature [°C], precipitation [mm/year], slope [°], drainage [-], physical soil fertility represented by Texture [-], share of coarse fragments [vol%] and soil depth [cm] and chemical soil fertility represented by the three substantial elements Nitrogen [%], Phosphorus [ppm] and Potassium [ppm], CEC [cmol(+)/kg clay], organic carbon (OC) [g/kg], pH [-] and salinity [dS/m].

The first scenario should display the status quo of agriculture in the study area. Having this, the model developed in LSE including the selected criteria, weighting and implementation of the software itself can be validated quickly afterwards by comparing the LSE output with available data from existing agriculture projects or green coverage maps as described later in section 6.2.3. When the validation did not yield successful results, the weights were edited in minor steps until the validation was satisfying. The validated model approach was then used to develop land suitability maps for the second scenario, which differs from the first scenario only in having the possibility of unlimited available water for irrigation. To display this in the modelling process, the precipitation was not included in the criteria in this scenario. A schematic visualisation of this process can be seen in Figure 18. The result came out to be that while the factors temperature, slope, course fragments (and precipitation for the unirrigated scenario), were set as limiting factors and hence not included in the weights, the remaining factors soil fertility, drainage properties, soil depth, and texture were equally weighted to approx. 25%.

Table 17: Values of sugar cane for the considered criteria

Criteria		Unit	S1	S2	S3	N
Topography and wetness	Temperature	°C	30-33	30-25.5 33-35.5	25.5-21 35.5-38	>21 >38
	Precipitation	mm/year	1600-2500	1200-1600	900-1200	<900
	Slope	°	0-3.492	3.492-5.241	5.241-8.749	>8.749
	Drainage	-	good; very good	moderate	somewhat poor	very poor, poor
Physical soil fertility	Texture*	-	C, L, SiCL, SiL, SCL, CL, SiC	(g)C, (g)L	SC, SL, (g)SL	(g)LS, LS
	Coarse fragments	Vol%	0-15	15-35	35-55	-
	Soil depth	cm	>100	50-100	25-50	<25
Chemical soil fertility	Total Nitrogen	%	>0.2	0.1-0.2	<0.1	-
	Available Phosphorus	ppm	>25	6-25	<6	-
	Potassium	ppm	>60	30-60	<30	-
	Apparent CEC	cmol (+)/ kg clay	>16	<16(-)	<16(+)	-
	Organic Carbon	g/kg	>10	10-6	>6	-
	pH	-	6.1-7.3	7.4-7.8 5.1-6.0	7.9-8.4 4.0-5.0	>8.4 <4
	Salinity	dS/m	<2	2-8	>8	-

The output of LSE is one map per crop showing the allocation of the available land to four suitability classes: very suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (N). Table 17 shows exemplary for sugarcane how the value ranges for the selected criteria for the MCDA are divided into the four suitability classes.

Table 18: Values of plant X for the considered criteria

Criteria		Unit	Suitable	Not suitable
Topography and wetness	Temperature	°C	>8	<8
	Precipitation	mm/year	>250	<250
	Slope	°	<3.43	>3.43
	Drainage	-	Very good, good moderate, somewhat excessive, excessive, imperfect, poor aeric	Very poor, poor
Physical soil fertility	Texture*	-	C<60s, SiC, Co, Si, SiL, CL, C<60v, SC, C>60s, L, LcS, fS, SL, LfS, C>60v, SCL	Cm, SiCm, cS
	Coarse fragments	Vol%	<55	>55
	Soil depth	cm	>10	<10
Chemical soil fertility	Total Nitrogen	%	>0.08	<0.08
	Available Phosphorus	ppm	>3	>3
	Potassium	ppm	>0.10	<0.10
	Apparent CEC	cmol (+)/ kg clay	>16	>16
	Organic Carbon	g/kg	<0.01	<0.01
	pH	-	4.5-8.5	>8.5 <4.5
	Salinity	dS/m	<6	>6

Accordingly, LSE was applied using collected data for sugarcane, potato, maize, faba beans, wheat, and cotton. In order to get an overview on the overall land suitability for agriculture, a hypothetical "plant X" was developed unifying the properties of all considered crops (See Table 18). The values for plant X were derived from a worst-case consideration in terms of "lowest possible requirements and highest possible tolerance for any of the commonly used plants to grow". For precipitation, for example, the range of values, the consideration of the corresponding is as "suitable" are displayed in Table 19. The values show that only sugarcane and wheat have thresholds for a maximum precipitation for which, after exceeding, the area would be considered as unsuitable. Since the remaining crops do not have such maximal values, the summarized plant X also does not have a maximal threshold. The lower threshold is thus determined by the crop with the lowest water demand, which is potato with 250 mm/yr.

Table 19: Considered crops and their corresponding suitable precipitation ranges

Crop	Suitable precipitation range [mm/year]
Sugarcane	900-2500
Potato	>600
Wheat	700-1500
Cotton	>500
Maize	>300
Faba Beans	>250
Plant X	>250

6.2.2 Results for the suitable area for agriculture

The land suitability yielded mostly uniform results. Some differences, however can be observed for potato, which is generally increasing the overall suitable area for irrigated agriculture in the study area. The output of the LSE software provides three different ranges for different levels of suitability and generates output areas for all of them. To increase the comprehensiveness of the result, the three classes were added to an overall suitable displayed in green color. Figure 25a shows the overall land suitability including the values for all selected crops in the status quo without any irrigation and only depending on precipitation as water source. The area considered as suitable for agriculture in this map extends through the center of the study area from north to south. The areas east of the Blue Nile and a strip of 50 km along the Ethiopian-Sudanese border in the most western part of the study area are considered as not suitable. Furthermore, the areas close to the Blue Nile and its tributaries are mostly considered as not suitable as well. From the 199.551 km^2 overall area of the Blue Nile basin accounts, approx. 33% or 65.853 km^2 have been classified as suitable for agriculture.

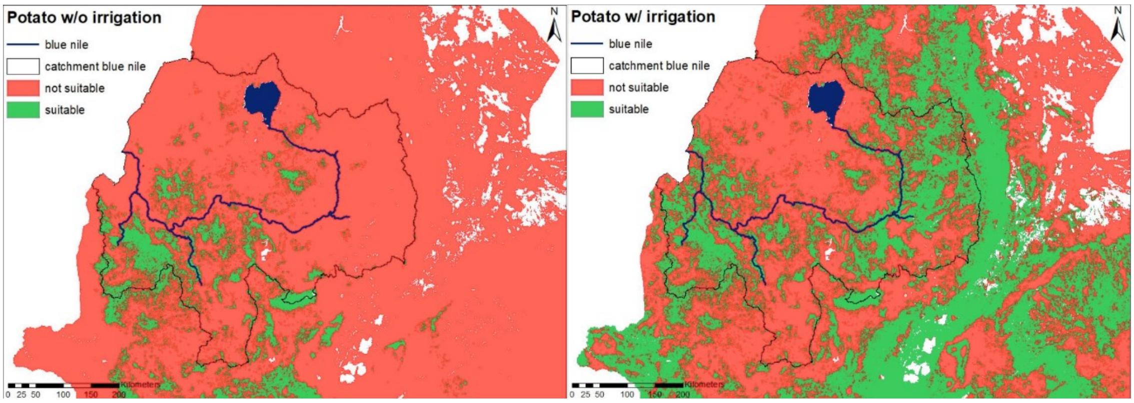

Figure 19: Land suitability for potato without (a) and with (b) irrigation

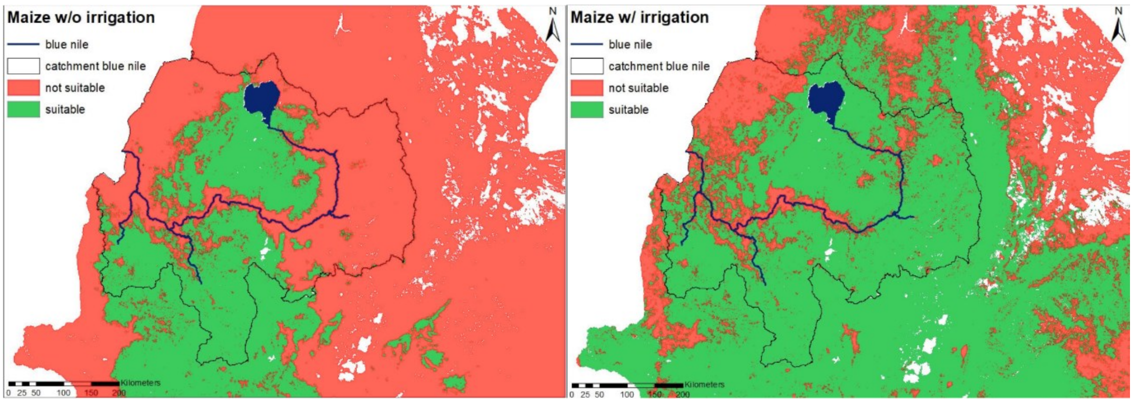

Figure 20: Land suitability for Maize without (a) and with (b) irrigation

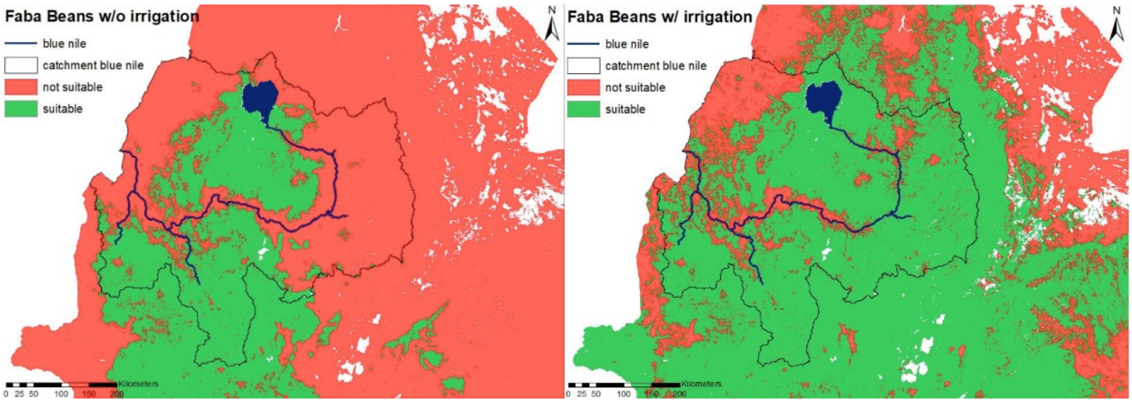

Figure 21: Land suitability for Faba Beans without (a) and with (b) irrigation

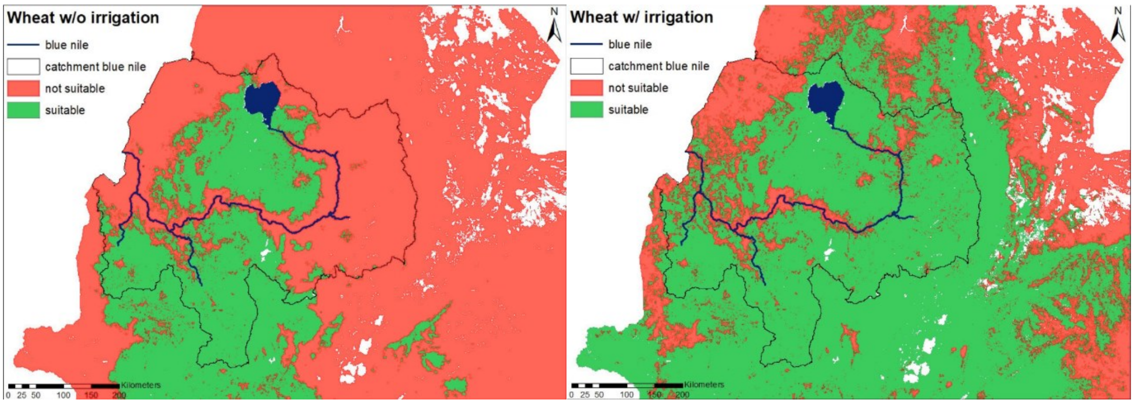

Figure 22: Land suitability for Wheat without (a) and with (b) irrigation

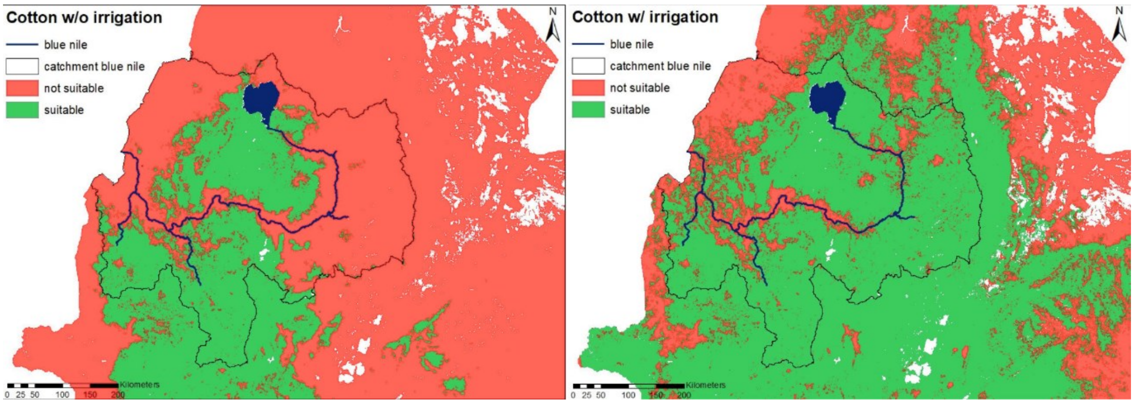

Figure 23: Land suitability for Cotton without (a) and with (b) irrigation

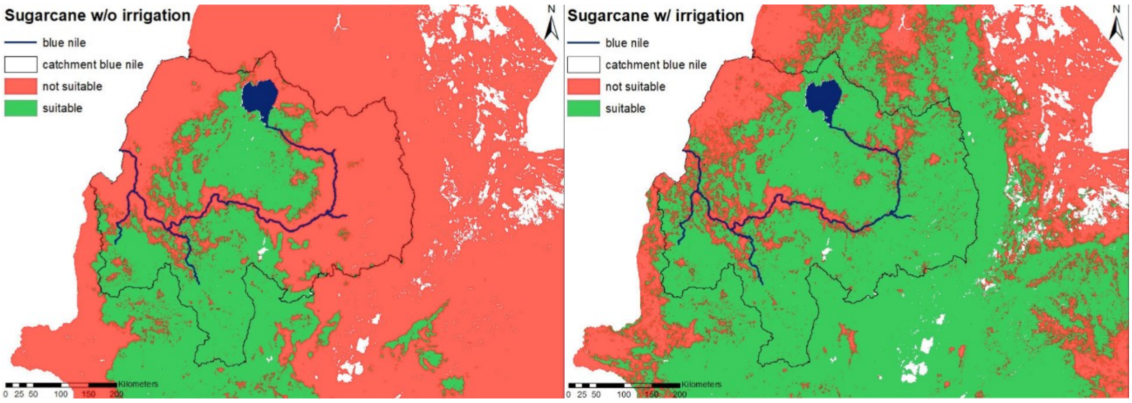

Figure 24: Land suitability for sugarcane without (a) and with (b) irrigation

Most of the LSE results showed reasonable results for both scenarios with and without irrigation as the selected crops also have comparable requirements in most of the criteria. The maps from Figure 19 to Figure 24 show the results for potato, maize, faba beans, wheat, cotton and sugarcane, whereas the figures a show the status quo with the dependency on precipitation and the figures b show the suitability for agriculture including irrigation. A common observation for all the crops is the area of the most eastern part of the basin, which is considered as unsuitable without irrigation but suitable with irrigation. Unchanged remains the area in the north-western study area as not suited. A closer look at the data of each of the criteria showed that the annual mean temperature in this area exceeds the maximal threshold of all plants' tolerance Similar to the overall estimation of plant X, the central area from north to south is suitable for agriculture in all the scenarios both in the status quo and the irrigation scenario.

Compared to all the other selected crops, potato showed very different results. As shown in Figure 19, the overall suitable area with only 14% of the whole basin is very low compared to the 44-45% of the other crops.

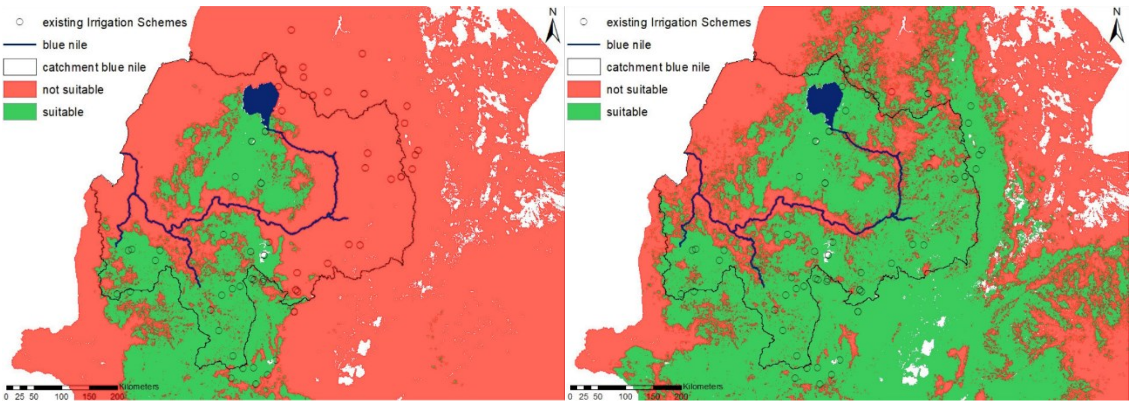

Figure 25: Overall land suitability (of plant X) under rainfed agriculture (a) and with irrigation (b)

In Figure 25a, the overall suitability of land for the irrigated agriculture, also labelled as scenario 2, is displayed. The map shows similarities to Figure 25b in terms of a large expansion of suitable land in the center of the study area from north to south. Irrigation has made big areas in the region more suitable for agriculture that were not suitable based on rainfed. However, the classification of the most western parts of the study area along the border to Sudan remains unsuitable as well as the area close to the river bodies. In scenario 2, 66% or 131.704 km^2 have been identified as suitable.

Table 20: Areas identified as (non-)suitable for agriculture with and without irrigation

Crop	Suitable area in Blue Nile basin w/o irrigation [km^2] (share)	Suitable area in Blue Nile basin with irrigation [km^2] (share)	Non-suitable area in Blue Nile basin w/o irrigation [km^2] (share)	Non-suitable area in Blue Nile Basin with irrigation [km^2] (share)
Potato	27.937 (14%)	69.843 (35%)	171.614 (86%)	129.708 (65%)
Maize	87.802 (44%)	155.650 (78%)	111.749 (56%)	43.901 (22%)
Faba beans	89.798 (45%)	155.650 (78%)	109.753 (55%)	43.901 (22%)
Wheat	89.798 (45%)	155.650 (78%)	109.753 (55%)	43.901 (22%)
Cotton	87.802 (44%)	155.650 (78%)	111.749 (56%)	43.901 (22%)
Sugarcane	87.802 (44%)	155.650 (78%)	111.749 (56%)	43.901 (22%)
Plant X	65.852 (33%)	131.704 (66%)	133.699 (67%)	67.847 (34%)

6.2.3 Validation of LSE Results

To validate the results of the model, a two-step approach was followed. Firstly, the generated results of suitable and not suitable land for agriculture were cross-checked with the available information of already existing farms in the study area, which are also displayed in Figure 14. However, as the available information on such projects is sparse on the one hand and mostly not up to date, a second step was done. Here, the Normalized Difference Vegetation Index (NDVI) was used.

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \qquad (160)$$

According to Copernicus Land Monitoring Core Service (LMCS) "*The Normalized Difference Vegetation Index (NDVI) is an indicator of the greenness of the biomes.*". (Copernicus Land Monitoring Service n.d.). In regard to equation 1, the NDVI is calculated by dividing the difference of the light reflectance of the near-infrared spectrum and the red spectrum through the sum of the same light spectra. (Fung and Siu 2000; Pettorelli 2013; USGS n.d.) The result is an index ranging from -1 to +1. Although there are several publications elaborating the possible level of detail of the NDVI results by splitting the index up in numerous groups of vegetation in different ecosystems (Goward et al. 1991; Fung and Siu 2000; Pettorelli 2013) the most common way of interpreting the NDVI values is done in three groups. The first group contains values approx. 0.1 or lower represents snow, barren rock or sand, the second group ranging from approx. 0.2 to 0.5 is made up of shrubs, grasslands, and senescing crops, and the third group from 0.6-0.9 represents dense vegetation. (USGS n.d.) However, as the distributions as per USGS contain gaps between the values, the groups were expanded on one hand and for the simple purpose of determining if the land cover is made up out of plants or of non-vegetative matter, also merged to a two groups distribution only displaying the availability of vegetation independent from its habitus. The threshold value for having vegetative matter as land cover was set to 0.2. To determine the lowest possible share in green coverage, data from 5th March 1999 were taken as the end of the dry period.

The NDVI data were taken from the online database "Global Forest Watch'' maintained by the World resources Institute with support of the ESA Climate Office. The acquired data displays the global NDVI values in a monthly interval in 1999. (World Resources Institute 2014)

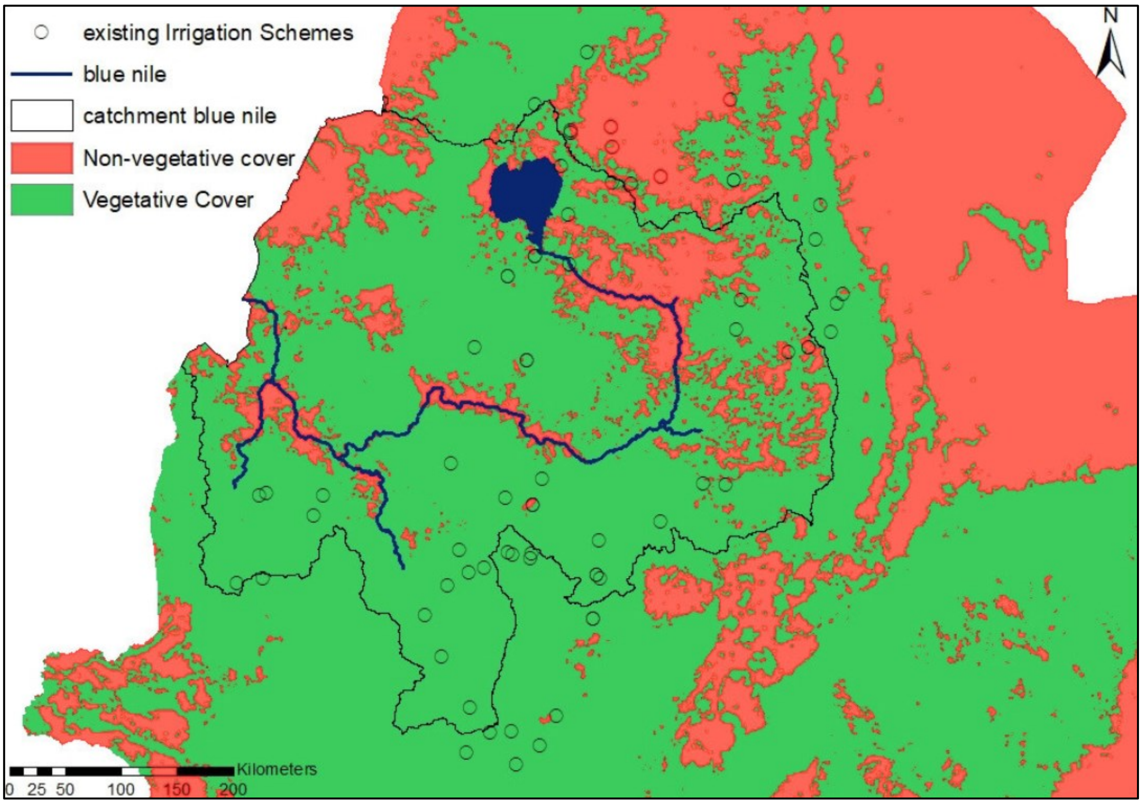

Figure 26: NDVI values of the Blue Nile Basin and the adjacent area

The NDVI-derived maps used for the validation process showed large similarities with the results generated for the case of intensified irrigation in the study area displayed in Figure 19b to Figure 24b. Comparing Figure 27 with the land suitability for sugar cane in Figure 28, the land identified by the model as unsuitable in the northwestern part of the study area also shows partially non-vegetative land cover. The areas near to the river(s) are also depicted as unsuitable, which is also supported by the vegetative land-cover map.

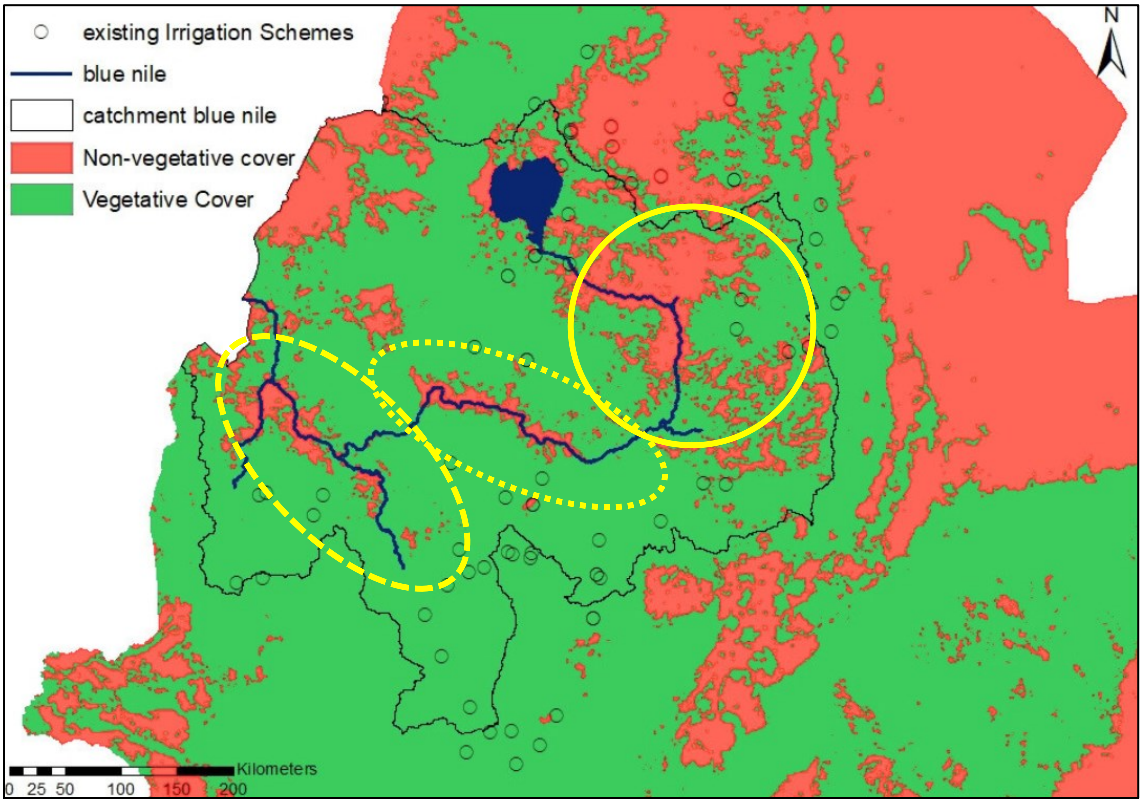

Figure 27: Vegetative land cover in the Blue Nile Basin through NDVI determination

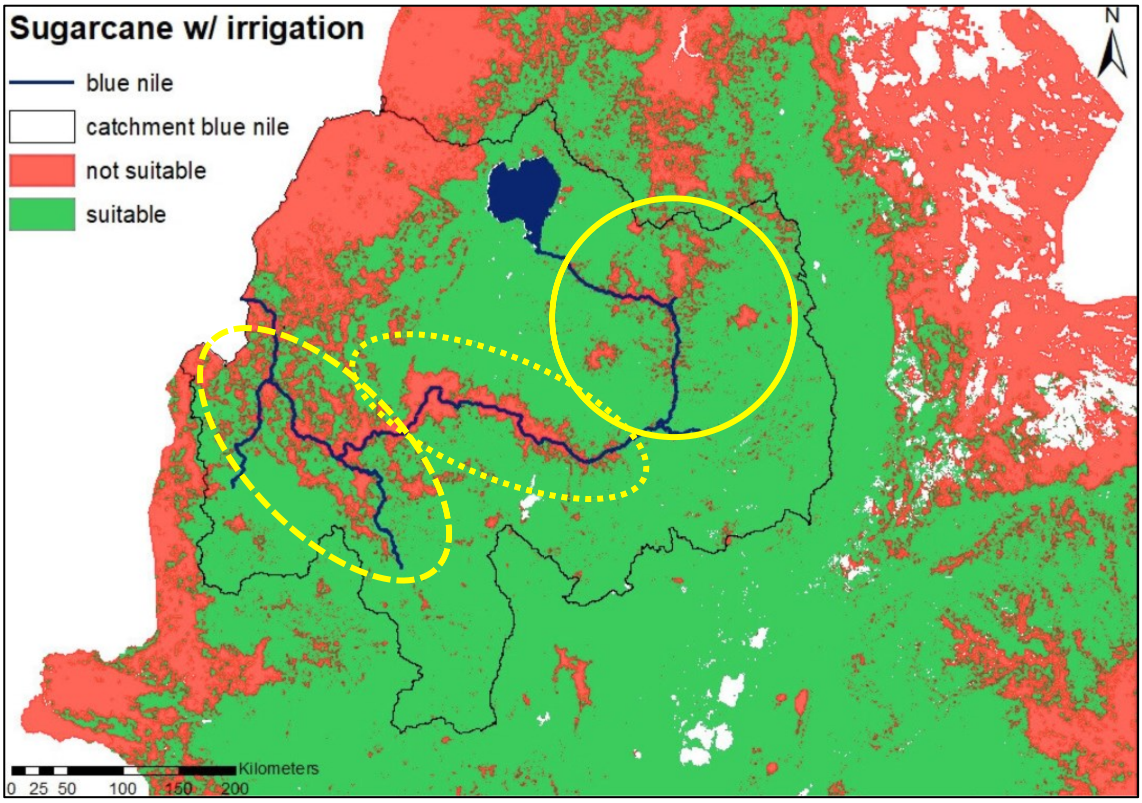

Figure 28: Land suitability for sugarcane with irrigation with focus areas

Areas to be pointed out to underline this is the larger area of the Bashilo River junction at the north eastern part of the study area (circle), the Blue Nile section between the Guder and Amhara junctions in the center (dotted circle) and the greater Dabus junction area in the western area of the study area (dashed circle). Another proof for the validity of the applied model is that the calculated share of the overall suitable land under current conditions (33%), displayed in Figure 25a, almost matches the share derived by recent studies with 33.9%. (Abtew and Dessu 2019)

The land assumed to be suitable for agriculture is confirmed by the numerous existing irrigation schemes (as also applied by (Kassie et al. 2022; Kau et al. 2023)) displayed in Figure 14 (Awulachew 2007; Nile Basin Initiative 2009). The most mentionable larger irrigation schemes which underline this statement are the Finchaa sugar Estate (Terefe and Sing 2019; Dinka 2016) and the Koga large scale irrigation scheme (Haile and Abebaw 2012; Birhanu et al. 2015; Asres 2016; Melesse and Abtew 2016; FAO 2018b) which were also consulted as sources for the crops chosen to be used for the land suitability evaluation. Further investigated areas like the Jabitenan District in the centre of the Blue Nile River basin (Nigussie et al. 2019) and the closer Lake Tana area. (Clarke et al. 2017)

As previously shown, both scenarios of land suitability with and without irrigation have the unsuitable area in the northwestern part of the study area close to the Sudanese border. Considering all the observed criteria, it is most likely that the temperature here is too high (>30°C), at least for the selected crops. Even though the mentioned area is located at the same latitudes as the considered suited eastern areas, the latter are part of the Ethiopian Highlands. Due to the corresponding reduction of temperature with rising altitude in the Ethiopian highlands, this can be verified. Although the NDVI maps considered for the validation show a higher share of vegetative coverage in this area. This indicates the general possibility to grow plants there. However, the single presence of vegetative matter does not promise an economic effect as e.g. shrubs or grasslands, which are also depicted as vegetative coverage, but the local circumstances to not allow a certain cultivation of locally common crops.

The unsuitable land near the river(s) and in the highlands is derived from the steepness of the surface. As for all crops, the maximum slope was specified as 3.434° (6%), the carved valleys are not the optimal agricultural land. However, as previously mentioned, steep slopes are not necessarily an obstacle since alternative ways like terrace-based agriculture are possible once the needed knowledge and technologies are available for the local communities.

The exception compared to all the other results is the potato as mentioned in the result section. Having a closer look at each criterion, the percentage of coarse fragments in the soil was identified as the source of low land suitability for potato (35%) while all the other crops have the uniform threshold value of 55%. Considering that all the other investigated plants grow above ground surface and the potato is the only root crop, this deviation from the rest of the crops is expected.

Table 21: Suited and unsuited areas for irrigated agriculture in the Blue Nile Basin before economic consideration

Climate Zone	Total Area [km^2]	Suited Area [km^2]	Unsuited Area [km^2]
Kola	74,110	26,510	47,350
Weynadega	80,180	63,160	13,530
Dega	41,880	37,510	4,320
Wurich	3,190	1,140	2,050
Total	199,360	128,320	67,250

6.2.4 Refinement through consideration of economic Influences

The previous results were based solely on the MCDA analysis as explained. These, however, only reflect the overall possibility of performing agriculture in the area without including economic factors like transport costs or the cost for electricity, the cost of water, and labor. To pay tribute to this dimension of agricultural suitability, a literature review was performed. Again, lacking reliable data was the main challenge in this task. The review showed that both water and electricity are charged very low, if at all. Especially for electricity, this will be explained later in this section. It can be said overall that these practices are done to support local farmers in increasing their crop yields and hence personal revenue. For electricity, this is due to the running GERD, which generates more than enough electricity to supply the local demand. For water, it is also the case that many farmers and the groups they are sometimes organized into have decentralized reservoirs to harvest rainwater and also hold back some of the river water from the wet season in late summer. The structures are mostly financed by fees to be part of this collective group and by revenues from loans the group is giving to farmers to expand their farms. (Belay and Bewket 2013). The water use itself seems to be free, however. This fits in with practices of other countries, as in Egypt, where water specifically used for irrigation is free of charge. Due to the facts mentioned above, costs for water and electricity were assumed to be negligible for the further research. The same was done for labor cost, as most of the farmers work on small-scale farms, so that they can be considered as one-person or family enterprises without actual salaries.

For the energy costs, focus was laid on the cost to pump the water throughout the hilly terrain, specifically from the Blue Nile River up to the Ethiopian Plateau. The energy cost was calculated by multiplying the required pumping energy in $\mathrm{kWh/m^3}$ with the electricity costs in USD/kWh and the water demand in $\mathrm{m^3/ha}$. The pumping energy E was calculated as follows according to (Carravetta et al. 2018):

$$E = \frac{(\rho \times g \times H)}{(3.6 \times 10^6 \times \eta)} \tag{161}$$

With $\rho = 1000\,\mathrm{kg/m^3}$ being the density of water, $g = 9.81\,\mathrm{m/s^2}$ being the earth acceleration, $H = 375.8\,\mathrm{m}$ being the maximal pumping height, and $\eta = 0.8$ being the average efficiency of commonly used centrifugal pumps (Martinez-Moore 2023; Rogers 2025). The first calculation results in 1.28 $\mathrm{kWh/m^3}$ (Kedir et al. 2022). With a more reasonable pumping height of 50 m, however, the average pumping energy is 0.17 $\mathrm{kWh/m^3}$, which was taken as the final results. As value for the water demand per ha, an average value of the estimated irrigation water demand described in section 1346.4 was used with 2.27 $\mathrm{m^3/ha}$. Using the literature value of 1.28 $\mathrm{kWh/m^3}$, the energy cost would be 0.025 USD/ha, using our own derived value of 0.17 $\mathrm{kWh/m^3}$, the energy cost would be at 0.004 USD/ha. As mentioned earlier, due to these very low values, energy cost will not be further considered.

For the transport costs, it was investigated what could be the longest distance to larger cities so that the revenue still stays positive. "Larger cities" were assumed to have more than 50,000 inhabitants. This was done assuming that these cities act as transport hubs for the crops to the world market. For the study area, 72 cities fitting in this framework were identified (CityPopulation 2022). As part of the case study, a set of 32 crops were identified, which will be explained in more detail in section 6.3.2 on the crop selection. Since it is impracticable or near impossible to elaborate the exact revenue, an average revenue for this set of crops was calculated. Additionally, it again became an obstacle to obtain reliable data for all crops for a longer period of time, so the time span was set to five years from 2018 to 2022. Most of the data could be retrieved from the FAO (20 crops), the remaining, however had to be retrieved from different literature sources. Due to that, a certain inaccuracy in the results needs to be assumed. For the revenue in USD per ton, the sum of the export values of the crops for the available years was divided by the export quantity for the years with available data.

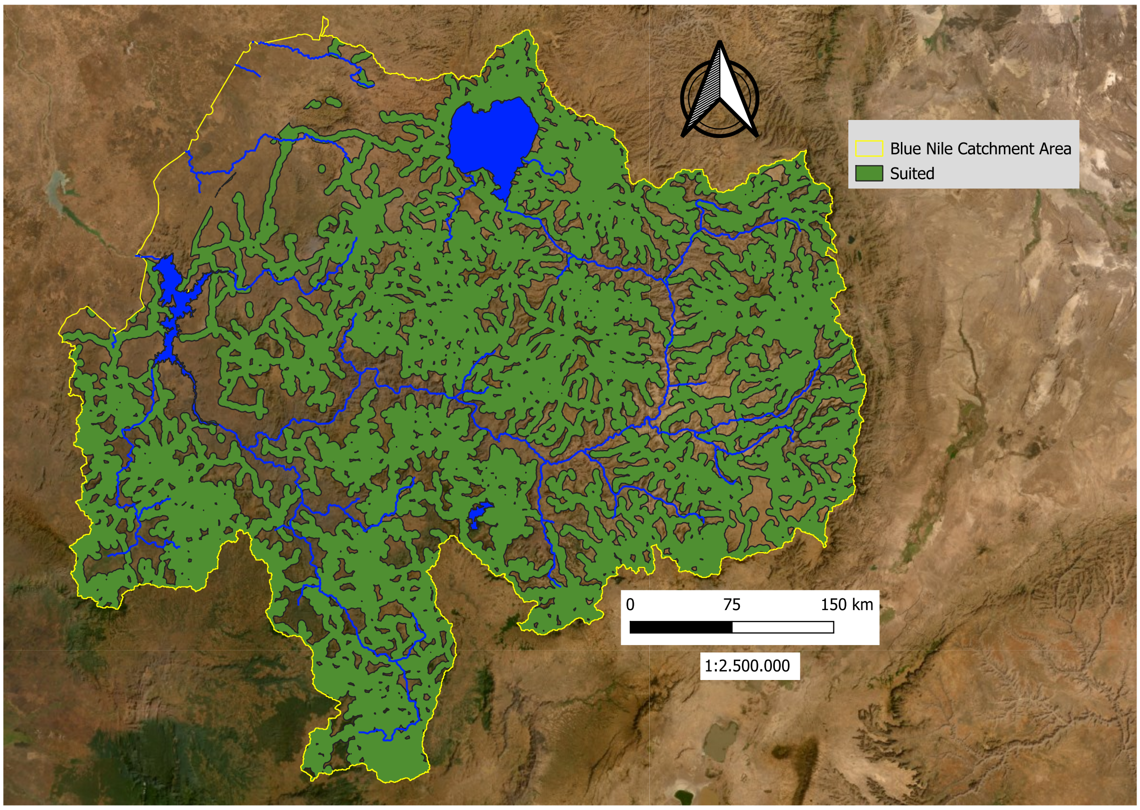

Figure 29: Suitable area according to the transport cost criterion

Table 22: Revenues for the selected crops

Crop	Revenue (USD/ton)	Source
Linseed	1,120.75	(FAO 2024)
Sorghum	690.89	
Head Cabbage	143.21	
Sesame	1,540.40	
Tomato	283.24	
Finger Millet	323.83	
Sweet Potato	148.57	
Onions	172.30	
Mango	193.23	
Banana	220.77	
Pepper	2,890.53	
Beans	719.46	
Garlic	542.97	
Maize	319.94	
Lentils	551.46	
Avocado	327.04	
Niger	533.08	
Faba Beans	577.27	
Field Peas	886.89	
Barley	1,713.15	
Chick Peas	756.70	
Niger	533.08	(Lin 2005)
Ground nut	594.00	(NAADS 2024)
Teff	814.67	(FAO 2018a)
Sugarcane	288.00	(SA FDA 2021)
Grass Peas	1,069.00	(Tridge 2025)
Haricot	353.00	(ECX 2024)
Enset	530.05	(BMG Foundation 2014)
Wheat	523.40	(USDA 2021)
Coffee Arabica	3,968.33	(UNDP 2024)
Taro	1,090.00	(Selina Wamucci 2024)
Chat	10,000.00	(Abdi 2022)
Gesho	137.61	(Bezabeh 2017)

The results for the revenues and the sources from which the export values and quantity were retrieved are displayed in Table 22, which indicated an overall mean revenue of 547.2 USD/ton.

To calculate the transport costs, it was assumed that a commonly used 12-ton truck with a fuel consumption of 0.25 l/km is used (Mykitiuk 2024) and that the current fuel cost is 0.8 USD/l (Global Petrol Prices 2025). Accordingly, the transport cost per km is 0.2 USD/km. According to (Kotzagioris 2022) approx. 10% of the revenue is dedicated to transport costs. To calculate the maximum transport distance, the 10% of the determined mean revenue is divided by the transport cost per km, which results in a transport distance of 280 km. Considering that the transport is a two-way trip, the maximum distance of the farm is 140 km.

To estimate the additional reduction of potential area for irritated agriculture, a buffer of the aforementioned 140 km was created around the cities. Additionally, it was assumed that the farms need to be adequately close to the road network, which was set to 2.5 km. The resulting layer is displayed in Figure 29. Table 23 shows the results for each of the four climate zones. It should be mentioned in the first place, that from the overall area of the study area, 452 km^2 were initially excluded due to factors making them unavailable for agriculture like water bodies and urban areas. These results are visualized in Figure 30.

Table 23: Suited and unsuited areas for irrigated agriculture in the Blue Nile Basin after economic consideration

Climate Zone	Total Area [km²]	Suited Area [km²]	Unsuited Area [km²]
Kola	74,110	15,380	58,730
Weynadega	80,180	46,632	33,548
Dega	41,880	31,654	10,226
Wurich	3,190	974	2,216
Total	**199,360**	**94,640**	**104,720**

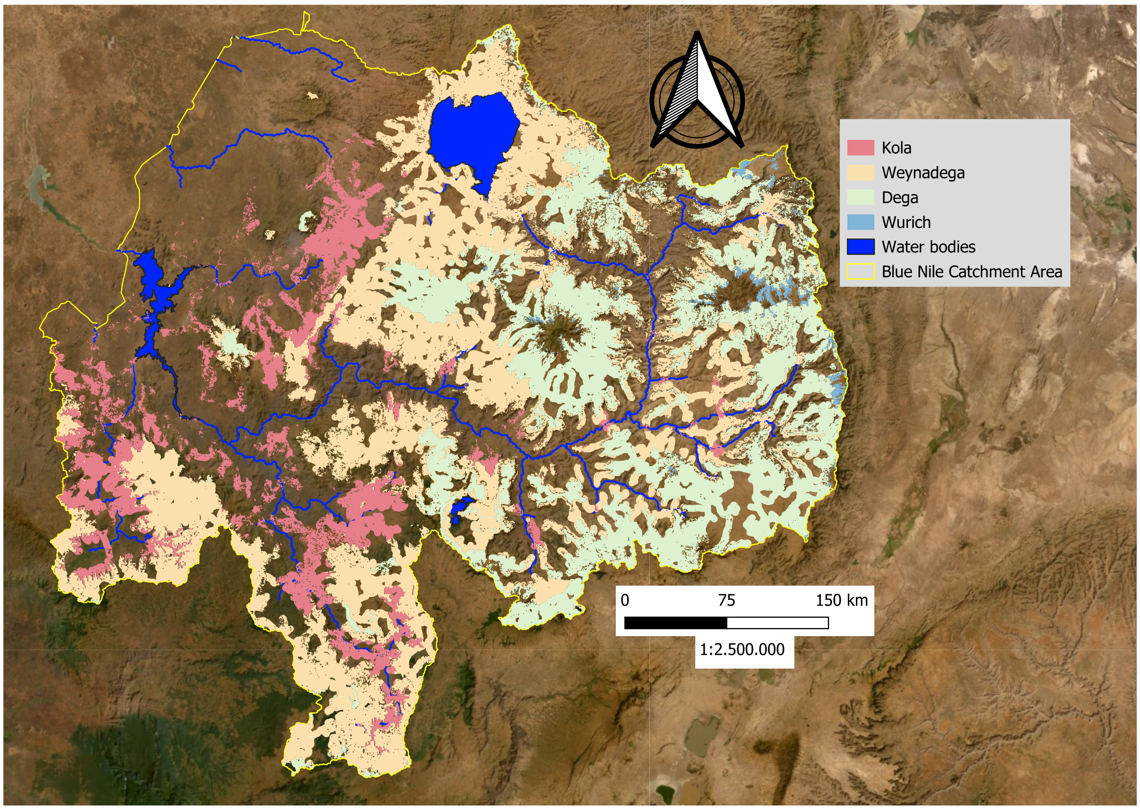

Figure 30: Land Suitability for agriculture in the four climate zones

The refinement reduced the area of suitable land throughout all four climate zones by 33,680 km^2 or approx. 26.25%. The key difference to the previous results is that not only the ecological possibility of performing agriculture is determined but also the economic feasibility to do so. For the climate zones, the refinement brought the largest reduction of 41.98% to the Kola zone followed by the Weynadega with 26.17%. Dega and Wurich share approx. the same percentual reduction by 14.79% and 14.56% respectively. Overall, about 47.47% of the available Blue Nile catchment area has been identified as suitable for irrigated agriculture. Compared to the previous results, two changes stand out. The first is the still occurring absence of suitable area in the north-eastern part of the study area. Figure 29 indicates that only one major street is crossing this area, which supports already the previous claim that this remote, desert-like area is not suited for agriculture. The areas highlighted with the yellow circles in Figure 28 have been even more thinned out after the refinement. This reflects the harsh terrain in this area and increases the plausibility of the suitability results because even if small areas per sé would be suitable for agriculture without proper connection to the road network, they would not be suitable in the end due to this reason.

Compared to the reviewed literature, the results can be categorized from two points of view. Some exceed previous results by far, as for example (Tsehayu 2008) determined 7,190.88 km^2 as suitable which is only about 7.6% of the result of this dissertation. This is remarkable since the authors of the mentioned study set their study area according to the

"Ethiopian part of Nile" which would include part of the northern located Ethiopian lands draining through the Black Nile/Atbara River. This should lead to larger values for suitable land. Restrictive suitability criteria lead to such comparably low results. In a more recent study, (Kassie et al. 2022) determined 19,165 km^2 and 10,364 km^2 suitable for irrigated agriculture with surface and groundwater respectively as water source. The value for irrigated agriculture makes up about 20.25% of the result of this dissertation. The reasons for the diversion in this case might be justified with different criteria considered in the MCDA process, as for example the proximity to river bodies and the precipitation deficit are included in the mentioned study with weights of 7% each. Both factors are not considered in this dissertation. (Cherinet et al. 2019) indicate 29.42% as cultivated land based on observation of the land cover change.
On the other hand, the outcome of the study performed by (Yalew et al. 2016) shows more similarities with this study. Combining the different suitability categories, the study finds 83.7% as suitable which is approx. 35% higher than determined through this dissertation. This is based mainly on the less restrictive categorization of slopes and share in coarse fragments (=stoniness) in the study from Yalew et al.. As mentioned earlier, specifically these two factors were the most limiting ones. In another study on the land cover change from (Tikuye et al. 2023), approx. 61.65% of the Blue Nile basin is identified as cropland.
The large variations in the estimations of the potential agriculturally useable area reflect the difficulty in solving this problem. By common sense, either very large or very low values trend to be incorrect. From comparison to available research, the result from this dissertation ranges in the upper part of the found range of values. The advantage of the overall approach followed in this dissertation however also is that even if the suitable area is considered to be inaccurate or wrong by other researchers, own workflows to determine the suitable area can be tried out and the approach pursued in the following sections can be performed without any adjustment except for the deviating area the overall irrigation water demand are calculated at the end of section 6.4.2.

6.3 Cropping Pattern design

For the estimation of the agricultural water demand, the previously determined land, which is considered as suitable for agricultural cultivation, is used. For the further process, however, the previously used selection of crops is now expanded. On one hand, this brings some fuzziness since the crops observed in the water demand estimation might not be reflected by the area considered as suitable for agriculture. Since this area, however, was generated as a worst-case scenario, meaning that the least resilient plants were used as benchmarks. Hence, it is assumed that, still, it is feasible to add more crops at this stage of the research. On the other hand, this adds benefit to the final results as with more crops observed, more detailed scenarios can be created and elaborated, giving the research as a whole more depth.

A reconsideration of the plants to include also leads to a repetition of previously already done steps regarding the suitability of certain plants. The first portioning was done depending on the climate zones. As previously mentioned, the study area is divided into four climate zones depending on the elevation of the terrain. In addition, plants have been selected based on their cultivation purpose. For this, it has been distinguished between cash crops, which are cultivated to sell the crops on the market for high revenue, and, on the other hand, the food crops, which are foreseen for own consumption by the farmers. For the final crop selection, these two dimensions have been combined so that for each climate zone there is a set of crops for both cash crops and food crops. Having these, the cropping patterns have been designed. During this, it was paid attention to the plausibility of the pattern in terms of growing period, time for harvesting, plowing, and sowing. In the following, the two processes mentioned above are described in more detail.

6.3.1 Climatic framework for crop selection

Since the climate in section 3.2 only was a broad cross-section over the whole Blue Nile basin, a closer look at each of the climate zones needs to be done to select suited plants and resulting cropping patterns for each zone. For this FAO data was accessed through CLIMWAT 2.0 for CROPWAT and WorldClim 2. The latter had to be done since the CLIMWAT data is based on data collected from weather stations which are not available in the Wurich zone. Hence, data from WorldClim 2 was used to interpolate the data for the study area. For whole Ethiopia, CLIMWAT includes 100 chronologically numbered weather stations distributed irregularly above the country throughout all agro-ecological zones except the Wurich zone as mentioned. This is also due to the limited availability of these zones. The data from the weather stations was exported to CROPWAT 8.0 by (Smith 2009) to display the data. The time period covered by the two databases ranges from 1971 to 2000 for CLIMWAT and from 1970 to 2000 for WorldClim 2. It happened to be that some of the data sets for this time span have been incomplete. In this case, the lacking data was supplemented with data from other time spans under the conditions that the time span covers at least 15 years. The data considered as necessary and hence were exported are the average precipitation as well as the average minimum, maximal, and the average overall temperature for each month, and also as an annual average value.

Starting from the climate zone with the lowest altitude, existing in the Blue Nile basin, the Kola zone lies between 500 and 1,500 masl. In the database used, 18 weather stations were located and used for the summary in Table 24. The average rainfall per year for the Kola zone is 779.7 mm. The average minimum temperature is 17.1°C and the average maximum temperature is 33.2°C. The average temperature of 25.1°C is calculated as the mean of the average maximum and the average minimum temperature.

Table 24: Summarized climate data of the Kola zone

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. rain	780	16	28	46	77	96	82	113	117	102	63	32	9
Av. T_{min}	17.1	15.5	16.7	17.7	17.7	17.9	18.3	18	17.8	17.9	16.8	15.7	15.1
Av. T_{max}	33.2	32.1	32.9	33.7	32.9	32.3	31.5	29.8	29.3	30.6	31.2	31	31.6
Av. T	25.1												

The summarized data shown in Table 25 from the above located climate zone Weynadega between 1,500 and 2,300 masl was generated from data from 56 weather stations. For the Weynadega Zone an average rainfall of 1,193.0 mm was calculated. The average minimum temperature was calculated to be 12.3°C and the average maximum temperature to be 25.7°C. The average of the two temperatures resulted in an average temperature of 19°C. In comparison to the Kola zone, the average annual rainfall is higher, and the average annual temperature is lower, which correlates with the well-known condition that temperature decreases with rising altitude.

Table 25: Summarized climate data of the Weynadega zone

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. rain	119.3	18	32	64	94	125	146	215	216	151	82	36	14
Av. T_{min}	12.3	10.7	11.8	12.9	13.5	13.4	13.1	13	12.9	12.8	11.9	10.9	10.4
Av. T_{max}	25.7	26.4	27.3	27.8	27.4	26.6	25.2	23.3	23.3	24.4	25.2	25.5	25.8
Av. T	19												

For the next climate zone Dega ranging from 2,300 to 3,200 masl, 23 weather stations were available in the database. The summarized data is shown in Table 26. From the weather station data follows an average annual rainfall of 1,135.0 mm, an average annual minimum temperature of 7.7°C and an average annual maximum temperature of 21.7°C. The average minimum and maximum temperature follow an annual average temperature of 14.7°C. The average annual temperature as well as annual minimum and maximum temperature are lower compared to those one of the Weynadega zone. The average rainfall of the Dega zone is about 130 mm lower than that one of the Weynadega zone.

Table 26: Summarized climate data of the Dega zone

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. Rain	113.5	26	41	75	103	100	105	207	204	132	83	39	20
av. T_{min}	7.7	6.3	7.1	8	8.9	8.9	8.5	8.9	8.8	8.3	7.4	6.2	5.5
av. T_{max}	21.7	22.9	22.8	23.3	22.8	22.8	22.1	19.9	19.7	20.5	20.8	21.2	21.8
av. T	14.7												

As already mentioned, the data for the Wurich zone covering all areas from 3,200 masl and above had to be retrieved from WorldClim since there weren't any weather stations available in CLIMWAT. To be able to access the data, the historically monthly climate data was downloaded for a spatial resolution of ~1 km^2 as raster data. To process the raster data, the software QGIS 3.32 Lima was used. QGIS was selected because the software is open-source and freely available, supporting the reproducibility claim of the results in this work.

In a first step, the original file, which covered the entire surface of the earth, was reduced to the larger study area, the Blue Nile basin. This was done on the one hand to reduce the computing capacity required for further processing, and on the other hand to increase the visualization of the results. For example, the average amount of precipitation in October worldwide in the period 1970-2000 is between 0-2,357 mm. For the same period, the average amount of precipitation in the larger study area only varies between 20-147 mm. Compared to the global range, this range is only at the lower end of the grey scale. Individual values within the study area become indistinguishable, because of very small color differences in the grey scale. By reducing the raster data to the larger study area, the range of the grey scale is also reduced to the values of the larger study area, which increases the contrasts between the individual values and makes them distinguishable from each other. As the individual climate zones are distinguished by their altitude above sea level, it is easy to differentiate between them. To do this, the digital elevation model (DEM) is divided into specific elevation sectors that correspond to the different climate zones. This subdivision is achieved by selecting these sectors and exporting them to new files, which then serve as mask layers. These mask layers are used to extract the areas associated with each climate zone from the precipitation and temperature grid. This allowed the climate data for the Wurich zone to be isolated from the rest of the data. To read out the data, five random points in the Wurich zone were selected and the climate data at these points were read out using the identify tool. For a better overview, the points were named based on nearby places or mountains. For all five locations, the minimum and maximum temperature and the average precipitation were read out for each month of the year. The average values were then calculated as before for the data from CLIMWAT. This resulted in the climate data shown in Table 27.

Table 27: Summarized climate data of the Wurich zone.

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. rain	106.3	16	25	62	69	104	114	326	348	134	56	27	12
Av. T_{min}	1.3	-0.4	0	0.9	2.6	2.5	2.7	3.3	3.1	2.4	0.2	-0.4	-0.9
Av. T_{max}	18.1	17.9	18.3	18.3	18.5	18.1	14.5	14.5	16.4	16.5	16.4	16.5	17
Av. T	9.7												

The data used to calculate the above climate data for the five stations shows unexpected patterns. In July and August, the average monthly minimum temperature is often one of the highest or the highest, while at the same time the average monthly maximum temperature is one of the lowest or the lowest in these two months. An expected trend would have been that the two average temperatures develop similarly, i.e. either both rise, or both fall in these months. This contrasting temperature development in the two months does not correspond to expectations and cannot be observed in the other climate data. The reasons for this could be incorrectly generated or incorrectly read data. It is also possible that this phenomenon occurs due to special circumstances such as the high geodetic altitude at which the climate zone is located. It can be observed that the average temperature decreases between the stations due to the altitude phenomenon mentioned. The amount of precipitation does not increase proportionally with the altitude at which the area is located. The calculated data fulfil the characteristics of the respective zone given by (Berhanu et al. 2014). All values are within the range given by the author.

6.3.2 Selection of the crops included in the evaluation

Based on the generated knowledge on the climate, the crops considered for the evaluation now can be selected. In addition to the weather dependencies, factors such as the cultivation plans, the classification type of the crop (food crop or cash crop) and also the plausibility of the crop were considered. Plausibility in this context means a farmer who targets to grow crops as food crops for its consumption would not cultivate in Ethiopia completely uncommon/unknown expensive crops, even though they might achieve high yields. Having the detailed knowledge on the monthly distribution of the precipitation and the temperature, a closer look can be made on the crops as well since for example it might be the case that a crop with a requirement of a certain minimal temperature is feasible to be cultivate according to annual temperature values but the monthly minimal values indicate that the temperatures are too low at one point of the cultivation period leading to wilting of the crop. To narrow down the selection of plants, the most common crops of private peasant holdings were collected from the 2014 E. C. Meher Season report by (The Federal

Democratic Republic of Ethiopia 2022b). “Meher” is the name in the local Amharic language for one of the two existing agricultural seasons, which is located in the rain season from June to September. The second, shorter and less productive season takes place during March and April and is called “Belg” (Tanto Hadado et al. 2009). In the report, the term “holding” is introduced, which stands for a legal small-scale agricultural business cultivating plants or keeping livestock for agricultural production, not depending on the type of organization, management, size or location. As the name of the report indicates, it only provides information for plants cultivated during the time period between June and September. Accordingly, information on irrigation agriculture in the dry season or during the Belg season is not included. Large-scale commercial agriculture is also not reflected by the report. This is done due to the comparably low significance of the large-scale businesses as they only demark about 5% of the overall annual gross agricultural production. The remaining 95% are accordingly produced by small-scale farmers. (The Federal Democratic Republic of Ethiopia 2022b) Furthermore, the assumption was made that the outcome of the crop selection is not fundamentally affected by not considering the Belg season crops. Subsequently, a set of crops was elaborated whose cultivation requirements from the report itself and other literature were collected. As mentioned in the description of the study area, the Blue Nile catchment area does not have any equivalent in the administration and is spreading over three federal districts, Amhara, Benishangul-Gumuz, and Oromia. Following the Meher report, the crop selected where categorized in seven groups, namely cereals (e. g. teff, wheat, maize) pulses (e. g. faba beans, field peas, chick-peas), oilseeds (e. g. niger, sesame), vegetables (e. g. lettuce, cabbage, tomatoes), root crops (e. g. beetroot, carrots, potatoes) fruit crops (e. g. avocados, bananas, mangoes), stimulant crops (e. g. chat, coffee, hops (gesho)), and additionally sugar cane and enset. It should be mentioned that is it getting not clear in the report if “hops” describes the common hop (=lat. Humulus lupulus) as is it for example used in brewing beer which does not count to the commonly cultivated crops or most likely the gesho (=lat. Rhamnus prinoides) which belongs to the classic crops in the area. (Jastrombek et al. 2022; Zewdu and Tsehai 2022; Adama et al. 2011) Both plants are substantially different in their type, but are used for the same purposes due to similarities in their properties. (Zewdu and Tsehai 2022; Berhanu et al. 2014) Due to that, it is assumed that gesho is meant in the Meher report and it will be used in the further research accordingly. Additional assumptions had to be made since in the report not all crops have been named with their botanical Latin name and are for example referred to depending on their color. Examples for this are green/red peppers, red/white chickpeas, and red/white haricot beans. For these crops, it was assumed that, independent from the color, the same crops were meant.

For the design of the cropping patterns, which will be explained in detail in the upcoming section. In the following, the selected crops for each of the seven groups, sugarcane and enset, will be explained in detail and their requirements are provided. The information given to each crop below is retrieved from Sys et al.’s, 1993 book on Land Evaluation, chapter three, “crop requirements” if not indicated otherwise. Sys et al. follow the terminology of land suitability evaluated as explained earlier, which consists of three four suitability classes: S1, S2, S3, and not suitable. To reflect the worst-case of agricultural extension, S3 has always been selected as these values indicated plant growth whenever possible. Of course, the requirements provided are very generalized and may not include limitation of cultivations due to local conditions. For better comparability, the water requirement for the crops is set equal to the amount of mm precipitation as it also is done in numerous literatures.

For the group of cereals, wheat, barley, sorghum, maize, teff, and finger millet have been selected. Wheat (*Triticum aestivum*) has a growing cycle of 100-250 days. An exacter estimation of this period depends on the type of wheat chosen. For cultivation, wheat needs mean temperatures between 8 and 30°C and 200 to 1,750 mm precipitation per growing cycle. In the early stages of the growing cycle, wheat is still resilient against frost. Barley (*Hordeum vulgare*) has a growing cycle of 120-156 days. Regarding temperature, barley is resilient compared to other plants as it can generally grow in areas with average temperatures below 20°C. For cultivation, barley needs a mean temperature of 2-28°C in the second month of the growing cycle and 8-36°C in the third month. During the fourth and fifth month, the mean temperature should be between 10-42°C. Precipitation requirements are 300-1,100 mm per growing cycle. Sorghum (*Sorghum bicolor*) has a growing cycle of 90-130 days. For cultivation, sorghum requires precipitation of 150-1,400 mm per growing cycle and mean temperatures between 15-32°C. Maize (*Zea mais*) has a growing cycle of 90-130 days. For cultivation, maize needs 300-1,600 mm of precipitation per growing cycle and mean temperatures of 14-40°C. Teff (*Eragrostis tef*) has a growing cycle of less than 85 to 90 days, depending on the exact type of the crop. (Ketema 1997) Due to its resilience towards water stress, it is extensively cultivated in Ethiopia. Over one growing cycle it only needs 300-500 mm of precipitation for cultivation. Mean temperature requirement range between 10-28°C. Finger millet (*Pennisetum americanum*) has a growing cycle of 70-105 days. For cultivation, finger millet requires precipitation of 300-600 mm per growing cycle and mean temperatures between 16-32°C.

Pulses are represented by chickpeas, faba beans, field peas, grass peas, haricot beans and lentils. Chickpeas (*Cicer orietunum*) have a growing cycle of 120-160 days. For cultivation, chickpeas require precipitation of 50-300 mm or more per growing cycle and mean temperatures between 12-28°C. Faba beans (*Vicia faba*) have a growing cycle of 120-150 days. (Subash et al. 2012) For cultivation, faba beans require precipitation of 650-1,000 mm per growing cycle and mean temperatures between 18-27°C. Field peas (*Lathyrus oleraceus*) have a growing cycle of 65-100 days. For cultivation, field peas require precipitation of 200-1,000 mm per growing cycle and mean temperatures between 8-25°C. In early stages of the cultivation, the plant can tolerate frost to a certain extent. Grass peas (*Lathyrus sativus*) have a growing cycle of approx. 125 days. (Dixit et al. 2016) For cultivation, grass peas require precipitation of 300-1,500 mm per growing cycle and mean temperatures between 15-24°C. Haricot beans (*Phaseolus vulgaris*) have a growing cycle of 85-110 days. (Worku 2015) For cultivation, haricot beans require precipitation of 300-400 mm per growing cycle and mean temperatures between 18-24°C. Lentils (*Vicia lens*) have a growing cycle of 80-135 days. For cultivation, lentils require precipitation of 350-550 mm per growing cycle and mean temperatures around 24°C.

Oilseeds are represented by groundnuts, linseed, niger and sesame. Groundnuts (*Arachis hypogaea*) have a growing cycle of 90-140 days. For cultivation, groundnuts require precipitation of 200-1,900 mm per growing cycle and mean temperatures between 10-34°C or more. Linseed (*Linum usitatissimum*) has a growing cycle of 165-190 days. For cultivation, linseed requires precipitation of 155-200 mm per growing cycle and mean temperatures between 10-27°C. (Singh and Chopra 2018) Niger (*Guizotia abyssinica*) has a growing cycle of 140-185 days depending on the specific species of this crop indigenous in Ethiopia. In some sources the plant is also called “nug” or “neug” For cultivation, niger requires precipitation of 500-2,000 mm per growing cycle and mean temperatures between 15-23°C. (Getinet and Sharma 1996) Sesame (*Sesamum indicum*) has a growing cycle of 70-100 days. For cultivation, sesame requires precipitation of 25-475 mm or more per growing cycle and mean temperatures between 16-18°C.

Vegetables are represented by Ethiopian cabbage, Head Cabbage, Peppers and Tomatoes. Ethiopian cabbage (*Brassica carinata*) has a growing cycle of 150-180 days. For cultivation, Ethiopian cabbage requires precipitation of 1,000-1,500 mm per growing cycle and mean temperatures between 10-25°C. (Braun 2010) Head cabbage (*Brassica oleracea*) has a growing cycle of 100-150 days. For cultivation, head cabbage requires precipitation of 250-1,000 mm or more per growing cycle and mean temperatures between 5-35°C. Nevertheless, head cabbage can tolerate temperatures of approx. -6°C for a short period of time (Ministry of Agriculture, Land and Marine Resources, Trinidad & Tobago 2010). Peppers (*Capsicum annuum*) have a growing cycle of 120-150 days. For cultivation, peppers require precipitation of 600-1,200 mm per growing cycle and mean temperatures between 14-28°C. Tomatoes (*Solanum lycopersicum esculentum*) have a growing cycle of 90-120 days. For cultivation, tomatoes require precipitation of 200-800 mm or more per growing cycle and mean temperatures between 13-35°C.

Root crops are represented by garlic, onions, potatoes, sweet potatoes, and taro. Garlic (*Allium sativum*) has a growing cycle of minimum 90 days. For cultivation, garlic requires precipitation of 600 mm or more per growing cycle and mean temperatures between 16-24°C. (Gebremeskel and Gebresamuel 2017) Onions (*Allium cepa*) have a growing cycle of 100-140 days. For cultivation, onions require precipitation of 250-1,600 mm per growing cycle and mean temperatures between 10-25°C. Potatoes (*Solanum tuberosum*) have a growing cycle of 90-120 days. For cultivation, potatoes require precipitation of 300-700 mm per growing cycle and mean temperatures between 8-30°C. Sweet potatoes (*Ipomoea batatas*) have a growing cycle of 120-150 days. For cultivation, sweet potatoes require precipitation of 550-1,270 mm per growing cycle and mean temperatures between 16-40°C. Taro (*Colocasia esculenta*) has a growing cycle of approx. 180 days. For cultivation, taro requires precipitation of 2,500 mm or more per growing cycle and mean temperatures between 21-27°C. (Moore and Lawrence 2003)

Fruit crops are represented by avocados, bananas, and mangos. As fruits are normally cultivated as permaculture, no actual growing cycle exists. It is assumed that fruit can be harvested once a year. For cultivating avocados (*Persea americana*) annual precipitation of 1,000-2,000 mm and mean annual temperatures between 14-24°C. (US Aid 2019) For cultivating bananas (*Musea spp.*) annual precipitation of 1,000-1,800 mm or more and mean annual temperatures of 14°C or more. For cultivating mangos (*Mangifera indica*), annual precipitation of 400-3,600 mm and mean annual temperatures between 24-27°C. (Bally 2006)

Stimulant crops are represented by chat, coffee arabica, and gesho. Chat (*Catha edulis*) just like the fruit crops mentioned above is a perennial crop. (Kandari et al. 2014) Because of that, a growing cycle cannot be indicated. For cultivation, chat requires precipitation of 500-1,200 mm per year and mean temperatures around 19°C. (Alkämper et al. 1990) Coffee arabica (*Coffea arabica*), just like the fruit crops mentioned above, is a perennial crop. (Déchamp et al. 2015) Because of that, a growing cycle cannot be indicated. For cultivation, arabica coffee requires precipitation of 800-2,000 mm or more per year and mean temperatures between 15-26°C. Gesho (*Rhamnus prinoides*) as well is a perennial crop, which is why a growing cycle cannot be indicated. (Teklay et al. 2016) It can endure a short period of frost (Orwa C. et al. 2009). For cultivation, gesho requires precipitation of 500-1,200 mm per year and mean temperatures between 14-22°C. (Amare et al. 2018)

Sugarcane (*Saccharum officinarum*) has a growing cycle of 270-2,100 days. For cultivation, sugarcane requires precipitation of approx. 1,300 mm per growing cycle and mean temperatures between 18-32°C or above.

Enset (*Ensete ventricosum*) also is one of the main crops cultivated in Ethiopia due to its richness in carbohydrates. Although it is a relative of the banana, the actual crop does not grow as a fruit as the banana but as a false stem like root crops. As indicated, a core part of the tree is the crop, in this case. Hence it needs about 3-12 years until the "crop" can be harvested. (Borrell et al. 2020) However, since there is no stage of ripeness in which the crop has to be harvested, enset is a very good way to secure food security since it can be harvested throughout the whole year, when it is necessary. A long-term cultivation plan needs to be in place because of the long growing period. For cultivation, enset requires precipitation of 1,100-1,500 mm per year and mean temperatures between 10-21°C. (Brandt et al. 1997; Tsegaye 2002).

6.3.3 Cropping patterns

Based on the gathered data for the climate and plausible crops to be cultivated, the cropping patterns for the different climate zones can be developed. All developed patterns cover a model area of one hectare arable land over a period of one year. The size of one hectare was chosen to ensure the scalability of the model. The time span of one year was chosen to be able to calculate the annual withdrawal of water from the river systems and to cover the different seasonal climatic conditions. Based on this model area, cropping patterns were then developed for the various scenarios. The factors which were considered while designing the cropping patterns are the four different climate zones with varying temperatures and rainfall that exist in the study area. Another factor is the irrigation type – full or supplemental irrigation. In addition, a distinction between cash and food/traditional crops is made for developed the patterns. The differentiation between cash crops and food crops was made based on the purpose of the crop. While cash crops are mainly cultivated to be sold on local or international markets, food crops serve the subsistence of the farmers. (Barbier 1987) For the study area, the crops commonly labelled as cash crops are cereals such as maize, teff and wheat; fruits such as avocados; oilseeds such like groundnut and sesame; pulses such as lentils, stimulants such as chat, gesho and coffee; vegetables such as tomatoes and sugarcane which is not belonging to any of the groups above. (Priyadarshan and Jain 2022; Kuma et al. 2016; Jiren et al. 2020; Wood and Habimana 2020; Ketema 1997; Megerssa and Alemu 2013). Both maize and wheat can be categorized in both groups and accordingly appear in both types of cropping patterns. This reflects the difficulty of clear distinction between food and cash crops. (Priyadarshan and Jain 2022)

It should be mentioned at this point that initially, when setting up the research, it was assumed the cash crops have higher water requirements than food crops, as it also appears to be the common opinion. This would also support the claim to determine the water withdrawals in a worst-case scenario. During the literature review and gathering of the plants' requirements, however, it was figured out that this is not always the case. Due to the clear difference in cash crop patterns being more water consuming than the food crop pattern, it is not given in all cases. The detailed description of the outcome of the water consumption is given in section 6.4.2.

The factors described above (irrigation type, climate zones, crop type) combined lead to a set of 16 cropping patterns. For the calculation of the water demand following the cropping pattern development, a plausible and feasible practice for this design needs to be elaborated. These need to be both economically viable and environmentally compatible. The cropping periods in the patterns have been intentionally arranged very close to each other in a sequential cropping approach without any recovery periods to pay tribute to the worst-case scenario intention. In this system, several crops are grown per year per area, one after the other. For some cropping pattern (e.g., in the Kola food crop supplemental irrigation cropping pattern in March and June) two crops share one month in case the growing cycles of the selected crops allow timewise sharing of the arable land. Avoiding large monocultures from the beginning, this approach also prevents the spreading of pests potentially leading to crop failures and soil exhaustion. (Francis and Porter 2017) To ensure this, each cropping pattern's area (one hectare) was schematically divided into three parts of the same size on which three crops are simultaneously and alternating cultivated over one year. The exception is the Wurich climate zone because the climatic conditions limit the potential crops to choose very severely. To stick to the overarching intent to display a worst-case scenario, a partial monoculture approach was chosen in which in two of the three thirds of the hectare only one crop is cultivated. In the status quo, the agriculture in the study area is highly dependent on precipitation so that crops can be cultivated successfully. The result is the two cropping seasons Belg and Kremt as described before. (FAO 2016) In the worst-case scenario, however, the precipitation is not limiting anymore. The commonly cultivated crops already were introduced in section 6.3.2. Table 28 below shows a summary of the typical crops in the different climate zones, which mostly show the same results.

Table 28: Main crops of the different climate zones

Climate Zone	Source: Hurni 1998	Source: Weldegerima et al. 2021
Kola	Sorghum, teff, finger millet, groundnut, niger	Sorghum, teff, finger millet, groundnut
Weynadega	Wheat, teff, maize, enset, niger, finger millet, barley	Wheat, teff, maize, enset, niger, finger millet, barley, sorghum, rice
Dega	Barley, wheat, pulses, niger	Barley, wheat, pulses, niger
Wurich	Barley	Barley

The only minor differences are that niger is considered as a main crop for the Kola zone as well by Hurni and Weldegerima adds rice to the set of crops for the Weynadega zone. Apart from that, both authors allocate finger millet, groundnut, niger, sorghum and teff to the Kola zone and barley, enset, finger millet, maize, niger, sorghum, teff and wheat to the Weynadega zone. Barley, niger, pulses and wheat are allocated to the Dega zone and Barley to Wurich. The fifth climate zone, Berha, is not part of the table as this zone does not occur in the study area as previously mentioned. Although the information provided by the literature in Table 28 is a good indicator for which plants can be used for a certain cropping pattern, specific growing conditions like temperature and water demand were considered. Additionally, other crops were added to the pool of possible crops specially for the cash crops scenario if their requirements match the local conditions to display future changes in the cultivated crops if the revenue is economically motivating. Regarding the temperature, it was assumed for the climate zones Kola, Weynadega, and Dega that if the annual average temperature lies above the minimal requirements of the plants, they can be cultivated. An exception of this assumption was made for the Wurich zone as the frost occurring in late fall and winter might not only reduce plant growth or yields, but also could completely destroy the crops if they are not tolerant against it. Frost resilience, however, is only known for a small share of crops like field pea, head cabbage, and wheat.

Since it is a major factor for the water demand if the crops are being fully irrigated or supplemental irrigated, it had to be determined for the cropping patterns under supplemental irrigation, during which months of the year irrigation happens, and during which months only rainfed agriculture is done. For simplification, only the Meher season from June to September was considered as the period of time in which irrigation is not necessary under supplemental irrigation. If irrigation was to be applied in the months directly before and after the Meher season (May and October), it was decided according to the occurring precipitation and the water demand of the crop cultivated during this time. If the precipitation would cover the water demand, no additional irrigation is applied, if not, it would be. Since the Belg season only covers about two months, which is very short to complete a full cultivation cycle, this season was neglected.

In the following, the cropping patterns for each of the four climate zones are introduced and explained in detail.

Kola

In this section, the four cropping patterns for the climate zone Kola are presented. Table 29 below displays the cropping pattern for the Kola zone under supplemental irrigation cultivating food crops. The months colored in grey (May-September) reflect the period of time without additional irrigation. The first row of the table shows the months of the year. The following rows show the crops in each month on one of the three thirds of the model area, with their minimum and maximum water requirement in millimeters. The last rows show the calculated minimum and maximum monthly water demand in millimeters per month resulting from the respective planting. For January, for example, the selected cultivation results in a minimum water demand of 34.4 mm per month and a maximum water demand of 195.5 mm per month. All the following cropping patterns for each climate zone are based on the same principle and can be read as described. The cropping patterns for each climate zone show first food-, then cash crops for the scenarios under supplemental irrigation, followed by the scenarios under full irrigation.

Table 29: Cropping pattern for the Kola zone with food crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Linseed		mix	Sorghum		mix	Head cabbage			Linseed		
2/3		Sorghum		Finger millet				Sweet potato				Sorghum	
3/3		Finger millet		Onion				Sorghum				Finger millet	
WR/m Onion [mm]	min	0	0	62.5	62.5	62.5	62.5	0	0	0	0	0	0
	max	0	0	400.0	400.0	400.0	400.0	0	0	0	0	0	0
WR/m sweet potato [mm]	min	0	0	0	0	0	0	137.5	137.5	137.5	137.5	0	0
	max	0	0	0	0	0	0	317.5	317.5	317.5	317.5	0	0
WR/m Sorghum [mm]	min	37.5	37.5	25.0	50.0	50.0	25.0	37.5	37.5	37.5	37.5	37.5	37.5
	max	350.0	350.0	233.3	466.7	466.7	233.3	350.0	350.0	350.0	350.0	350.0	350.0
WR/m finger millet [mm]	min	37.5	37.5	37.5	37.5	37.5	37.5	0	0	0	0	37.5	37.5
	max	200.0	200.0	200.0	200.0	200.0	200.0	0	0	0	0	200.0	200.0
WR/m linseed [mm]	min	28.2	28.2	14.1	0	0	0	0	0	0	28.2	28.2	28.2
	max	36.4	36.4	18.2	0	0	0	0	0	0	36.4	36.4	36.4
WR/m Head cabbage [mm]	min	0	0	0	0	0	35.7	71.4	71.4	71.4	0	0	0
	max	0	0	0	0	0	142.85	285.7	285.7	285.7	0	0	0
WD [mm]	min	34.4	34.4	46.4	50.0	50.0	53.6	82.1	82.1	82.1	67.7	34.4	34.4
	max	195.5	195.5	283.8	355.6	355.6	325.4	317.7	317.7	317.7	234.6	195.5	195.5

Following this, Table 30 shows the cropping pattern for the Kola zone under supplemental irrigation, cultivating cash crops. It can be seen here that compared to the table above, the month October also stays unirrigated since the water demand of the crops selected for this pattern is fully covered by the precipitation.

Table 30: Cropping pattern for the Kola zone with cash crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		mix	Groundnuts				Tomato				Sesame		
2/3		Tomato				Sesame			mix	Groundnuts			
3/3		sugarcane											
WR/m tomato [mm]	min	50.0	50.0	50.0	50.0	0	50.0	50.0	50.0	50.0	0	0	0
	max	200.0	200.0	200.0	200.0	0	200.0	200.0	200.0	200.0	0	0	0
WR/m sugar cane [mm]	min	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0
	max	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
WR/m ground nuts [mm]	min	22.2	44.4	44.4	44.4	44.4	0	0	22.2	44.4	44.4	44.4	44.4
	max	211.1	422.2	422.2	422.2	422.2	0	0	211.1	422.2	422.2	422.2	422.2
WR/m sesame [mm]	min	12.5	0	0	0	25.0	25.0	25.0	12.5	0	25.0	25.0	25.0
	max	237.5	0	0	0	475.0	475.0	475.0	237.5	0	475.0	475.0	475.0
WD [mm]	min	64.9	68.1	68.1	68.1	59.8	61.7	61.7	64.9	68.1	59.8	59.8	59.8
	max	276.2	267.4	267.4	267.4	359.1	285.0	285.0	276.2	267.4	359.1	359.1	359.1

Table 31 and Table 32 display the cropping patterns for the same climate zone Kola, both under full irrigation cultivating food and cash crops. For both patterns, perennial crops were selected (banana and mango) in addition to seasonal crops to cover all twelve months of a year.

Table 31: Cropping pattern for the Kola zone with food crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Onion			Sorghum			Sweet potato					Onion
2/3		Mango											
3/3		Banana											
WR/m onion [mm]	min	62.5	62.5	62.5	0	0	0	0	0	0	0	0	62.5
	max	400.0	400.0	400.0	0	0	0	0	0	0	0	0	400.0
WR/m sweet potato [mm]	min	0	0	0	0	0	0	137.5	137.5	137.5	137.5	137.5	0
	max	0	0	0	0	0	0	317.5	317.5	317.5	317.5	317.5	0
WR/m sorghum [mm]	min	0	0	0	50.0	50.0	50.0	0	0	0	0	0	0
	max	0	0	0	466.7	466.7	466.7	0	0	0	0	0	0
WR/m banana [mm]	min	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3
	max	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
WR/m mango [mm]	min	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3
	max	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
WD [mm]	min	59.7	59.7	59.7	55.5	55.5	55.5	84.7	84.7	84.7	84.7	84.7	58.7
	max	283.3	283.3	283.3	305.6	305.6	305.6	255.8	255.5	255.8	255.8	255.8	283.3

Table 32: Cropping pattern for the Kola zone with cash crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Tomato				Teff			Groundnut				
2/3		Teff		Groundnuts					Tomato				Teff
3/3		Sugarcane											
WR/m tomato [mm]	min	50.0	50.0	50.0	50.0	0	0	0	50.0	50.0	50.0	50.0	0
	max	200.0	200.0	200.0	200.0	0	0	0	200.0	200.0	200.0	200.0	0
WR/m sugar cane [mm]	min	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0
	max	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
WR/m ground nuts [mm]	min	0	0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
	max	0	0	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0	380.0
WR/m teff [mm]	min	150.0	150.0	0	0	150.0	150.0	150.0	0	0	0	0	150
	max	183.3	150.0	0	0	183.3	183.3	183.3	0	0	0	0	183.3
WD [mm]	min	103.3	103.3	66.7	66.7	100.0	100.0	100.0	66.7	66.7	66.7	66.7	100.0
	max	187.8	187.8	253.3	253.3	247.8	247.8	247.8	253.3	253.3	253.3	253.3	247.8

Weynadega

In this section, the four cropping patterns for the climate zone Weynadega are presented. In Table 33, the cropping pattern for the Weynadega zone under supplemental irrigation, cultivating food crops, and in Table 34, cash crops are displayed. For these two patterns, the period without irrigation is the same for both approaches.

Table 33: Cropping pattern for the Weynadega zone with food crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Grass peas				Pepper					Teff		
2/3		Pepper		Haricot beans			Garlic				Pepper		
3/3		Enset											
WR/m teff [mm]	min	0	0	0	0	0	0	0	0	0	150.0	150.0	150.0
	max	0	0	0	0	0	0	0	0	0	183.3	183.3	183.3
WR/m enset [mm]	min	91.7	91.7	91.7	91.7	91.7	91.7	91.7	91.7	91.7	91.7	91.7	91.7
	max	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0
WR/m pepper [mm]	min	120.0	120.0	0	0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0
	max	240.0	240.0	0	0	240.0	240.0	240.0	240.0	240.0	240.0	240.0	240.0
WR/m grass peas [mm]	min	25.0	25.0	25.0	25.0	0	0	0	0	0	0	0	0
	max	125.0	125.0	125.0	125.0	0	0	0	0	0	0	0	0
WR/m garlic [mm]	min	0	0	0	0	0	150.0	150.0	150.0	150.0	0	0	0
	max	0	0	0	0	0	300.0	300.0	300.0	300.0	0	0	0
WR/m haricot beans [mm]	min	0	0	100.0	100.0	100.0	0	0	0	0	0	0	0
	max	0	0	133.3	133.3	133.3	0	0	0	0	0	0	0
WD [mm]	min	128.9	128.9	122.2	122.2	103.9	128.9	128.9	128.9	128.9	120.6	120.6	120.6
	max	263.3	263.3	227.8	227.8	166.1	263.3	263.3	263.3	263.3	182.8	182.8	182.8

Table 34: Cropping pattern for the Weynadega zone with cash crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Maize					Wheat				Lentils		
2/3		Avocado											
3/3		Coffee arabica											
WR/m Maize [mm]	min	60.0	60.0	60.0	60.0	60.0	0	0	0	0	0	0	0
	max	320.0	320.0	320.0	320.0	320.0	0	0	0	0	0	0	0
WR/m Lentils [mm]	min	0	0	0	0	0	0	0	0	0	116.7	116.7	116.7
	max	0	0	0	0	0	0	0	0	0	183.3	183.3	183.3
WR/m Wheat [mm]	min	0	0	0	0	0	50.0	50.0	50.0	50.0	0	0	0
	max	0	0	0	0	0	437.5	437.5	437.5	437.5	0	0	0
WR/m Coffee arabica [mm]	min	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	max	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7
WR/m Avocado [mm]	min	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3
	max	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7
WD [mm]	min	70.0	70.0	70.0	70.0	70.0	66.7	66.7	66.7	66.7	88.9	88.9	88.9
	max	217.8	217.8	217.8	217.8	217.8	257.0	257.0	257.0	257.0	172.2	172.2	172.2

In Table 35 and Table 36, the cropping patterns for the Weynadega zone under full irrigation with food and cash are displayed.

Table 35: Cropping pattern for the Weynadega zone with food crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Faba beans	Niger				Pepper				Faba beans		
2/3		Teff			Sesame		mix	Wheat			mix	Field peas	
3/3		Taro											
WR/m Niger [mm]	min	0	41.7	41.7	41.7	41.7	0	0	0	0	0	0	0
	max	0	166.7	166.7	166.7	166.7	0	0	0	0	0	0	0
WR/m Faba beans [mm]	min	54.2	0	0	0	0	0	0	0	0	54.2	54.2	54.2
	max	83.3	0	0	0	0	0	0	0	0	83.3	83.3	83.3
WR/m Taro [mm]	min	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3
	max	416.7	416.7	416.7	416.7	416.7	416.7	416.7	416.7	416.7	416.7	416.7	416.7
WR/m Pepper [mm]	min	0	0	0	0	0	120.0	120.0	120.0	120.0	0	0	0
	max	0	0	0	0	0	240.0	240.0	240.0	240.0	0	0	0
WR/m Wheat [mm]	min	0	0	0	0	0	25.0	25.0	25.0	25.0	25.0	0	0
	max	0	0	0	0	0	218.8	218.8	218.8	218.8	218.8	0	0
WR/m sesame [mm]	min	0	0	0	25.0	25.0	12.5	0	0	0	0	0	0
	max	0	0	0	475.0	475.0	237.5	0	0	0	0	0	0
WR/m field peas [mm]	min	0	0	0	0	0	0	0	0	0	40.0	40.0	40.0
	max	0	0	0	0	0	0	0	0	0	200.0	200.0	200.0
WR/m teff [mm]	min	150.0	150.0	150.0	0	0	0	0	0	0	0	0	0
	max	183.3	183.3	183.3	0	0	0	0	0	0	0	0	0
WD [mm]	min	137.5	133.3	133.3	91.7	91.7	121.9	126.1	126.1	126.1	109.2	114.2	114.2
	max	227.8	255.6	255.6	352.8	352.8	371.0	364.7	364.7	364.7	306.3	300.0	300.0

Table 36: Cropping pattern for the Weynadega zone with cash crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Maize					Wheat				Lentils		
2/3		Coffee arabica											
3/3		Chat											
WR/m maize [mm]	min	60.0	60.0	60.0	60.0	60.0	0	0	0	0	0	0	0
	max	320.0	320.0	320.0	320.0	320.0	0	0	0	0	0	0	0
WR/m lentils [mm]	min	0	0	0	0	0	0	0	0	0	116.7	116.7	116.7
	max	0	0	0	0	0	0	0	0	0	183.3	183.3	183.3
WR/m wheat [mm]	min	0	0	0	0	0	50.0	50.0	50.0	50.0	0	0	0
	max	0	0	0	0	0	437.5	437.5	437.5	437.5	0	0	0
WR/m coffee arabica [mm]	min	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	max	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7	166.7
WR/m chat [mm]	min	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WD [mm]	min	58.9	58.9	58.9	58.9	58.9	55.6	55.6	55.6	55.6	77.8	77.8	77.8
	max	195.6	195.6	195.6	195.6	195.6	234.7	234.7	234.7	234.7	150.0	150.0	150.0

Dega

In this section, the four cropping patterns for the climate zone Dega are presented. Table 37 and Table 38 show the patterns for supplemental irrigation for food and cash crops. For both patterns, the months May to October are left unirrigated as the rainfall is high enough to sufficiently supply the crops with water.

Table 37: Cropping pattern for the Dega zone with food crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Potato				Onion				Barley			
2/3		Chick peas				Field peas			Potato				Chick peas
3/3		Barley				Chick peas					Field peas		
WR/m potato [mm]	min	75.0	75.0	75.0	75.0	0	0	0	75.0	75.0	75.0	75.0	0
	max	175.0	175.0	175.0	175.0	0	0	0	175.0	175.0	175.0	175.0	0
WR/m onion [mm]	min	0	0	0	0	62.5	62.5	62.5	62.5	0	0	0	0
	max	0	0	0	0	400.0	400.0	400.0	400.0	0	0	0	0
WR/m chick peas [mm]	min	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	0	0	10.0
	max	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	0	0	60.0
WR/m barley [mm]	min	37.5	37.5	37.5	37.5	0	0	0	0	37.5	37.5	37.5	37.5
	max	375.0	375.0	375.0	375.0	0	0	0	0	375.0	375.0	375.0	375.0
WR/m field peas [mm]	min	0	0	0	0	66.7	66.7	66.7	0	0	66.7	66.7	66.7
	max	0	0	0	0	333.3	333.3	333.3	0	0	333.3	333.3	333.3
WD [mm]	min	40.8	40.8	40.8	40.8	46.4	46.4	46.4	49.2	40.8	59.7	59.7	38.1
	max	203.3	203.3	203.3	203.3	264.4	264.4	264.4	211.7	203.3	294.4	294.4	256.1

Table 38: Cropping pattern for the Dega zone with cash crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Tomato				Groundnuts				Wheat			
2/3		Gesho											
3/3		Groundnuts				Wheat				Tomato			
WR/m wheat [mm]	min	0	0	0	0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
	max	0	0	0	0	437.5	437.5	437.5	437.5	437.5	437.5	437.5	437.5
WR/m gesho [mm]	min	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WR/m ground nuts [mm]	min	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	0	0	0	0
	max	475.0	475.0	475.0	475.0	475.0	475.0	475.0	475.0	0	0	0	0
WR/m tomato [mm]	min	50.0	50.0	50.0	50.0	0	0	0	0	50.0	50.0	50.0	50.0
	max	200.0	200.0	200.0	200.0	0	0	0	0	200.0	200.0	200.0	200.0
WD [mm]	min	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max	258.3	258.3	258.3	258.3	337.5	337.5	337.5	337.5	245.8	245.8	245.8	245.8

In Table 39 and Table 40, the cropping patterns for this climate zone under full irrigation for food and cash crops are displayed.

Table 39: Cropping pattern for the Dega zone with food crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Barley				Onion				Potato			
2/3		Potato				Barley				Onion			
3/3		Onion				Potato				Barley			
WR/m potato [mm]	min	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0
	max	175.0	175.0	175.0	175.0	175.0	175.0	175.0	175.0	175.0	175.0	175.0	175.0
WR/m onion [mm]	min	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5
	max	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
WR/m barley [mm]	min	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5
	max	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0
WD [mm]	min	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3
	max	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7

Table 40: Cropping pattern for the Dega zone with cash crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Wheat				Teff			Tomato				Wheat
2/3		Gesho											
3/3		Groundnuts				Wheat					Teff		
WR/m wheat [mm]	min	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	0	0	40.0
	max	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	350.0	0	0	350.0
WR/m teff [mm]	min	0	0	0	0	150.0	150.0	150.0	0	0	150.0	150.0	150.0
	max	0	0	0	0	183.3	183.3	183.3	0	0	183.3	183.3	183.3
WR/m gesho [mm]	min	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WR/m ground nuts [mm]	min	50.0	50.0	50.0	50.0	0	0	0	0	0	0	0	0
	max	475.0	475.0	475.0	475.0	0	0	0	0	0	0	0	0
WR/m tomato [mm]	min	0	0	0	0	0	0	0	0	50.0	50.0	50.0	50.0
	max	0	0	0	0	0	0	0	0	200.0	200.0	200.0	200.0
WD [mm]	min	43.9	43.9	43.9	43.9	77.2	77.2	77.2	43.9	43.9	80.6	80.6	77.2
	max	308.3	308.3	308.3	308.3	211.1	211.1	211.1	216.7	216.7	161.1	161.1	211.1

Wurich

In this section, the four cropping patterns for the climate zone Wurich are presented. As mentioned above, the list of possible crops to cultivate in this climate zone is very limited due to partially low temperatures below the freezing point of water. Field pea, head cabbage, and wheat tolerate frost, while both field pea and wheat only tolerate frost in early stages and head cabbage for a short period throughout the whole cultivation period. In contrast to the lower climate zones where low amounts of precipitation are limiting unirrigated agriculture, in Wurich, the opposite is the case for July and August. Precipitation amounts of 326.4 mm and 347.8 mm respectively exceeding the upper limit of the tolerable water amount of many crops. Because of these limitations, the sets of crops to be cultivated for the cash crop and food crop pattern are the same. The difference that remains is the number of months in which the plants are irrigated. Still, an exception had to be made for the months with excessive rainfall. It was assumed that this circumstance does not harm the plants. Since the values for the monthly water requirements and upper limits for examples for chat are derived from annual values, it seems plausible that the average monthly values do not present sharp values. Table 41 and Table 42 show the patterns for supplemental irrigation for food and cash crops. For the patterns with food crops, the months May to October are left unirrigated, for the patterns with cash crops, the months May to September are left unirrigated.

Table 41: Cropping pattern for the Wurich zone with food crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Head cabbage		Field pea				Wheat				Head cabbage	
2/3		Head cabbage		Potato				Barley				Head cabbage	
3/3		Head cabbage		Barley				Wheat				Head cabbage	
WR/m potato [mm]	min	0	0	75	75	75	75	0	0	0	0	0	0
	max	0	0	175.0	175.0	175.0	175.0	0	0	0	0	0	0
WR/m head cabbage [mm]	min	187.5	187.5	0	0	0	0	0	0	0	0	187.5	187.5
	max	750.0	750.0	0	0	0	0	0	0	0	0	750.0	750.0
WR/m wheat [mm]	min	0	0	0	0	0	0	100.0	100.0	100.0	100.0	0	0
	max	0	0	0	0	0	0	875.0	875.0	875.0	875.0	0	0
WR/m barley [mm]	min	0	0	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	0	0
	max	0	0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	0	0
WR/m field peas [mm]	min	0	0	66.7	66.7	66.7	66.7	0	0	0	0	0	0
	max	0	0	333.3	333.3	333.3	333.3	0	0	0	0	0	0
WD [mm]	min	62.5	62.5	59.7	59.7	59.7	59.7	45.8	45.8	45.8	45.8	62.5	62.5
	max	250.0	250.0	294.4	294.4	294.4	294.4	416.7	416.7	416.7	416.7	250.0	250.0

Table 42: Cropping pattern for the Wurich zone with cash crops under supplemental irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Wheat											
2/3		Wheat											
3/3		Gesho											
WR/m gesho [mm]	min	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WR/m wheat [mm]	min	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	max	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0
WD [mm]	min	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0

In Table 43 and Table 44, the cropping patterns for this climate zone under full irrigation for food and cash crops are displayed.

Table 43: Cropping pattern for the Wurich zone with food crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Head cabbage		Field pea				Wheat				Head cabbage	
2/3		Head cabbage		Potato				Barley				Head cabbage	
3/3		Head cabbage		Barley				Wheat				Head cabbage	
WR/m potato [mm]	min	0	0	75.0	75.0	75.0	75.0	0	0	0	0	0	0
	max	0	0	175.0	175.0	175.0	175.0	0	0	0	0	0	0
WR/m head cabbage [mm]	min	187.5	187.5	0	0	0	0	0	0	0	0	187.5	187.5
	max	750.0	750.0	0	0	0	0	0	0	0	0	750.0	750.0
WR/m wheat [mm]	min	0	0	0	0	0	0	100.0	100.0	100.0	100.0	0	0
	max	0	0	0	0	0	0	875.0	875.0	875.0	875.0	0	0
WR/m barley [mm]	min	0	0	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	0	0
	max	0	0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	375.0	0	0
WR/m field peas [mm]	min	0	0	66.7	66.7	66.7	66.7	0	0	0	0	0	0
	max	0	0	333.3	333.3	333.3	333.3	0	0	0	0	0	0
WD [mm]	min	62.5	62.5	59.7	59.7	59.7	59.7	45.8	45.8	45.8	45.8	62.5	62.2
	max	250.0	250.0	294.4	294.4	294.4	294.4	416.7	416.7	416.7	416.7	250.0	250.0

Table 44: Cropping pattern for the Wurich zone with cash crops under full irrigation

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1/3		Wheat											
2/3		Wheat											
3/3		Gesho											
WR/m gesho [mm]	min	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7
	max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
WR/m wheat [mm]	min	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	max	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0	875.0
WD [mm]	min	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0

6.4 Estimation of Agricultural Water demand

In this chapter, the process of the estimation of the agricultural water demand is described. It starts with a complete explanation of the approach followed, and afterwards with a combined description of the results of the different steps.

6.4.1 Approach

Based on the cropping patterns developed in section 6.3.3, the volume of the water needed for irrigation is calculated. First of all, the average monthly water demand for each plant is calculated by dividing the overall water demand per growing cycle, which is the commonly used unit in literature, by the duration of a growing cycle. Here again, the growing cycles commonly given in days were transformed into the equivalent duration in months while assuming that one month equals 30 days. If two crops share a month like linseed and sorghum, and sorghum and head cabbage in the Kola food crop supplemental irrigation cropping pattern in March and June, the mean values of the two crops' monthly water demand were used for this month. Both the lower and the upper limits of the monthly water requirement were listed in the cropping patterns. If the literature values did not indicate a maximum requirement, this was assumed to be twice the minimum requirement. In case perennial crops (e.g. trees) were selected, their monthly water requirement was calculated by dividing the given yearly values by twelve months. It is assumed that for perennial crops, the minimum monthly water requirement can be undercut in a month as long as the average annual rainfall covers the annual requirement of the plant. If the maximum water requirement was given as "greater than" in the literature, the numerical values provided were utilized to obtain clear limits. The qualifier "greater than" was disregarded. For example, for garlic and taro, the minimal precipitation values only could be found in literature with “greater than” values. Here, it was assumed that the maximum values are double the minimum ones to fill the data gaps. Having both minimal and maximal water requirements, the range of potential withdrawn water can be displayed in the end. To calculate the minimal and maximal values without losses for the whole pattern, each of the values was multiplied by 1/3 since, as explained earlier, the areas for the cropping pattern are equally divided into three parcels. Without losses in this case means that losses due to seepage, inaccurate irrigation, or evaporation are not considered yet. After adding these weighted values up, the result displays the minimal or maximal water requirement as shown in the equation below:

$$WD_{area,\mathrm{min/max,wo\ losses}} = \frac{1}{3} * (WR_{1,\mathrm{min/max}} + WR_{2,\mathrm{min/max}} + WR_{3,\mathrm{min/max}}) \qquad 162$$

Whilst $WDarea, min/max\ , wo\ losses$ is the minimal or maximal weighted water demand of the crops on the model area without losses in mm and $WR_{\mathbf{1/2/3,min/max}}$ is the minimal or maximal water requirement of each crop on the model area in mm. When using the calculated value $WD_{\mathrm{area,min/max,wo\ losses}}$ it is assumed that the water is optimally distributed during irrigations and that there is no competition between the plants regarding water intake. Irrigation was only scheduled in months when the weighted minimum water demand exceeded the rainfall. Considering this, some crops might have higher water requirements than there is precipitation in some months, but irrigation is not scheduled because the total weighted water demand is still covered by precipitation.

Having determined the water demand of the plants without losses, the factor losses can be added. This needs to be done because not all water applied to the field will reach the plants, so an additional amount of water needs to be added so that no water shortage for the plants occurs due to these losses. For doing so, the three main irrigation techniques, surface, sprinkler, and drip irrigation, are considered to take losses due to seepage or evaporation into account. Combining these three options with the number of cropping patterns, the Irrigation Water Demand (IWD) for 48 scenarios is determined. Alike the WD, the IWD is first calculated on a monthly basis and added up afterwards to an annual water demand so that the water withdrawal can be set in relation to the yearly discharge of the Nile River. For the calculation of the monthly IWD, the minimal and maximal water demand of the plants without losses is reduced by the monthly precipitation.

$$IWD_{\mathrm{area,min/max,wo\ losses}} = WD_{\mathrm{area,min/max,wo\ losses}} - \mathrm{precipitation} \qquad 163$$

Whilst IWD is the minimal or maximal irrigation water demand of the area without losses in mm, WD is the minimal or maximal water demand of the crops without losses in mm. For losses considered in this research are the seepage losses due to unsealed canals due to pervious construction material as well as evaporation since typically the canals do not have a cover. Secondly, each irrigation method has an efficiency rate which considers water losses due to leakage, evaporation or inaccurate water distribution, which leads to infiltration of the water into deeper soil layers where it is not available for the plant. For the canal-related losses, the FAO indicates conveyance efficiencies for different types of soil type in canals with earthen sealing layers and for lined canals of different lengths as displayed in Table 45.

Table 45: Indicative values of the conveyance efficiency for adequately maintained canals (FAO 2023b)

	Earthen canals			Lined canals
Canal length / Soil type	Sand	Loam	Clay	
Long (>2000 m)	60%	70%	80%	95%
Medium (200-2000 m)	70%	75%	85%	95%
Short (< 200 m)	80%	85%	90%	95%

For the calculation of the actual irrigation water demand including the losses, a combined factor for the irrigation efficiency needs to be determined. Due to the lack of a definition of the term “adequately maintained” by the FAO, as well as due to lack of information on the soil type the earthen canals are coated with, and also the length of the canal from the abstraction point to the field is not distinguishable for this broad overview. To again take the worst-case scenario in account, the conveyance efficiency was assumed to be 60% which is the lowest amongst the combinations shown in Table 45. A side effect supporting the worst-case scenario claim but not primarily intended is the assumption that due to rising temperature because of global warming, the evaporation from open canals will increase in future decades. Hence choosing the lowest possible efficient according to the FAO is feasible. (NASA 2025) The irrigation methods and their respective field application efficiencies have already been explained in detail in section 2.3. In short, the indicative values provided by the (FAO 2023b) will be used, which are 60% for furrow irrigation, 75% for drip irrigation, and 90% for drip irrigation. The resulting irrigation efficiencies $\eta_{\text{irrigation}}$ for the three methods are 36% for furrow irrigation, 45% for sprinkler irrigation and 54% for drip irrigation.

For the calculation of the irrigation water demand including losses, the previously determined irrigation water demands without losses are divided by the irrigation efficiencies:

$$IWD_{\text{area,min/max,incl. losses}} = \frac{IWD_{\text{area,min/max,incl. losses}}}{\eta_{\text{irrigation}}} \qquad 164$$

The result $IWD_{\text{area,min/max,incl. losses}}$ is the amount of water that can be seen at the least amount of water withdrawn over one year from a water source to realize the specific cropping pattern with the different sets of crops and their water requirements. These water demands are of course still linked to the different climate zones, which have different shares in the Blue Nile basin. To determine the irrigation water demand for the whole basin, each of the four climate zone values with the same remaining factors (rainfed/irrigated agriculture, irrigation method, cash/food crop) need to be added up. The size of the suitable areas for several crops and for the worst case constructed plant X was determined in an earlier step of the research outlined in section 6.2.2. Table 46 shows the suited and not suited areas of plant X distributed over the climate zones.

Table 46: Suitable and not suitable areas for irrigated agriculture of the occurring climate zones

Climate Zone	Total Area [km²]	Suited Area [km²]	Not suited Area [km²]
Kola	74.110	15.380	58.730
Weynadega	80.180	46.632	33.548
Dega	41.880	31.654	10.226
Wurich	3.190	974	2.216
Total	199.360	94.640	104.720

The total area of the Blue Nile basin is given as 199.360 km^2, out of which 94.640 km^2 are suitable for irrigation. The largest area of the basin is in the Weynadega zone with 80.180 km^2, and the largest area of the suitable area is also located in this zone with 46.632 km^2. The area share in the Wurich zone is the smallest at 3.190 km^2, and the suitable area share in this zone is also the smallest at 974 km^2. Having these, the overall minimal and maximal irrigation water demands including losses for each climate zone can be calculated as follows:

$$oIWD = \sum IWD_{\text{area, min/max, incl.losses}} * area_{\text{climate zone}} \quad (165)$$

Whilst $\Sigma IWD_{\text{area, incl.losses,min/max}}$ is the sum of the minimal and maximum irrigation water demands per scenario and year, $area_{\text{climate zone}}$ is the area considered as suited per climate zone in km^2 and $oIWD$ is the minimal or maximal overall irrigation water demand for one year and scenarios in BCM.

6.4.2 Results

Based on the approach described in section 6.4.1, the water demands for the 48 defined technical scenarios are calculated step by step starting with the irrigation water demand for the different climate zones without losses for cash or food crop and under supplemental/full irrigation. Then, the losses due to conveyance and inefficiency of the irrigation techniques are added. In the results, both the minimum and maximum irrigation water demand/ overall irrigation water demand are indicated to give a range in which the actual water withdrawal might be in. Afterwards, the IWD is assumed to be the minimal IWD for the supplemental irrigation scenarios or in other words, for these scenarios only the minimal water demand of the plants will be considered for the calculation of the IWD. Accordingly, the maximum IWD for the full irrigation scenarios or these, only the maximal water demand of the plants will be considered for the calculation of the IWD. Having this clear distinction made, the results for the supplemental and full irrigation are clearer and differentiable. This effect will, after all be evident around the rainy Meher season, when no irrigation will be necessary for the supplemental irrigation scenarios and IWD will be zero for these months in which there is enough precipitation to cover the water demand of the plants. In general, the IWD is determined by subtracting the precipitation from the water demand of the plants.

Kola

The results of the IWD for the Kola zone with a food cropping pattern under supplemental irrigation are displayed in Table 47.

Table 47: IWD for Kola with and without losses for food crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		779.8	16.2	27.8	45.9	77.2	96.4	81.6	112.5	116.6	102.2	62.9	31.6	8.7
WD [mm]	min	34.4	34.4	46.4	50.0	50.0	53.6	82.1	82.1	82.1	67.7	34.4	34.4	
	max	195.5	195.5	283.8	355.6	355.6	325.4	317.7	317.7	317.7	234.6	195.5	195.5	
IWD w/o losses [mm]	min	18.2	6.6	0.4	0	0	0	0	0	0	4.8	2.8	25.7	
	max	179.3	167.6	237.9	278.3	0	0	0	0	0	171.7	163.9	186.8	
IWD furrow [mm]	min	50.6	18.3	1.1	0	0	0	0	0	0	13.3	7.8	71.4	
	max	498.1	465.6	660.8	773.2	0	0	0	0	0	476.9	455.2	518.9	
IWD sprinkler [mm]	min	40.4	14.7	0.9	0	0	0	0	0	0	10.7	6.2	57.1	
	max	398.4	372.5	528.6	618.5	0	0	0	0	0	381.5	364.1	415.1	
IWD drip [mm]	min	33.7	12.2	0.7	0	0	0	0	0	0	8.9	5.2	47.6	
	max	332.0	310.4	440.5	515.5	0	0	0	0	0	317.9	303.4	345.9	

Line one indicates the average precipitation in the respective climate zone for a year of split up for the months for reference. Line two indicates the minimal and maximal water demand of the combination of plants for the respective cropping pattern, in this case, the Kola zone, food cropping pattern under supplemental irrigation according to the literature for reference. Following the approach elaborated on in section 6.4.1, the IWD without losses due to conveyance and irrigation is indicated in line three and the lines four to six indicate the IWD with losses depending on the specific irrigation technique. From July to September, the minimum water demand has its maximal value with 82.1 mm each and minimal value with 34.4 mm each in the months from November to February. For the maximum water demand, the maximum occurs during April and May with 355.6 mm and the minimum occurs during November to February with 195.5 mm each. As earlier explained, it was intended to construct the cropping patterns in that way, that during the rainy season, no additional irrigation would be done. Accordingly, like for this example, the minimal and IWD for the months are always zero independent from any losses. If the IWD demands would not be zero, additional irrigation would be necessary. For the scenario displayed in Table 47, this is the case for the month April to September for the minimal water demand and from May to September for the maximal IWDs independent from the losses. Even though the maximal IWDs are not covered by the precipitation, the nature of this scenario under supplemental irrigation causes that no irrigation will be done in the "irrigation-free" months. In contrast to that, the period from November to April is irrigated again, leading to values for the maximal IWD for example IWD without losses of 278.3 mm in April, which is at the same time the maximal value for the maximum IWD. The maximum for the minimal IWDs without losses occurs in December when 25.7 mm have to be irrigated in addition to the water coming from the precipitation.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the additional minimal water demand occurs in March with 1.1 mm and the maximal water demand in December with 71.4 mm respectively. For the maximal water demand, the values are the lowest in November with 455.2 mm and the highest in April with 773.2 mm. Due to the rising efficiency, the IWDs are becoming smaller with the remaining two techniques. For the sprinkler irrigation, the minimum of the minimal IWD occurs in March with 0.9 mm and the maximum with 57.1 mm in December. The minimum of the maximal IWD occurs in 364.1 mm in November and the maximum in April with 618.5 mm. For drip irrigation, the minimum of the minimal IWD occurs in March with 0.7 mm and the maximum with 47.6 mm in December. The minimum of the maximal IWD occurs in 303.4 mm in November and the maximum in April with 515.5 mm.

Table 48 shows the results for the same scenario as above, with the difference that in this case cash crops are chosen for the cropping pattern instead of food crops.

Table 48: IWD for Kola with and without losses for cash crops under supplemental irrigation

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]	779.8	16.2	27.8	45.9	77.2	96.4	81.6	112.5	116.6	102.2	62.9	31.6	8.7
WD [mm]	min	64.9	68.1	68.1	68.1	59.8	61.7	61.7	64.9	68.1	59.8	59.8	59.8
	max	276.2	267.4	267.4	267.4	359.1	285.0	285.0	276.2	267.4	359.1	359.1	359.1
IWD w/o losses [mm]	min	48.7	40.3	22.2	0	0	0	0	0	0	0	28.2	51.1
	max	260.0	239.6	221.5	190.2	0	0	0	0	0	0	327.5	350.4
IWD furrow [mm]	min	135.4	111.9	61.6	0	0	0	0	0	0	0	78.3	142.0
	max	722.3	665.5	615.2	528.3	0	0	0	0	0	0	909.6	973.3
IWD sprinkler [mm]	min	108.3	89.6	49.3	0	0	0	0	0	0	0	62.6	113.6
	max	577.9	532.4	492.1	422.6	0	0	0	0	0	0	727.7	778.7
IWD drip [mm]	min	90.2	74	41.1	0	0	0	0	0	0	0	52.2	94.7
	max	481.5	443.6	410.1	352.2	0	0	0	0	0	0	606.4	648.9

Here, the period in which no irrigation will be done was set from May to October. The precipitation values remain the same as in Table 47 since only the selection of crops and due to that the water demand on the values building on this changed. This applies for all upcoming Kola-related tables. The minimum of the minimal water demand happens to be in May, November, and December with 59.8 mm each and the maximum with 68.1 mm from February to April. The maximum water demand ranges from 267.4 mm from February to April and in September to 359.1 mm in May and from October to December. Again, the water demand cannot be covered by the precipitation except for the minimal water demand in April. To cover the maximal water demand in April, 190.2 mm water has to be irrigated which is the minimal amount of the maximal values. Throughout the rest of the irrigated period, the minimum of the minimal values lies at 22.2 mm in March and the maximum at 51.1 mm in December. The minimum of the maximal irrigation demand lies in April as mentioned above. The maximum lies in December with 350.4 mm.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in March with 61.6 mm and the maximum of the minimal water demand in December with 142.0 mm respectively. For the maximal water demand, the values are the lowest in April with 528.3 mm and the highest in December with 973.3 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in March with 49.3 mm and the maximum with 113.6 mm in December. The minimum of the maximal IWD occurs with 422.6 mm in April and the maximum in December with 778.7 mm. For drip irrigation, the minimum of the minimal IWD occurs in March with 41.1 mm and the maximum with 94.7 mm in December. The minimum of the maximal IWD occurs with 352.2 mm in April and the maximum in December with 648.9 mm.

Table 49 shows the IWD for the Kola zone for food crops under full irrigation.

Table 49: IWD for Kola with and without losses for food crops under full irrigation

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]	779.8	16.2	27.8	45.9	77.2	96.4	81.6	112.5	116.6	102.2	62.9	31.6	8.7
WD [mm]	min	59.7	59.7	59.7	55.5	55.5	55.5	84.7	84.7	84.7	84.7	84.7	58.7
	max	283.3	283.3	283.3	305.6	305.6	305.6	255.8	255.5	255.8	255.8	255.8	283.3
IWD w/o losses [mm]	min	43.5	31.9	13.8	0	0	0	0	0	0	21.8	53.1	51
	max	267.2	255.5	237.4	228.3	209.1	224.0	143.3	139.3	153.7	192.9	224.2	274.7
IWD furrow [mm]	min	120.9	88.5	38.2	0	0	0	0	0	0	60.4	147.5	141.8
	max	742.1	709.7	659.4	634.3	580.9	622.1	398.1	386.9	426.9	535.8	622.8	763.0
IWD sprinkler [mm]	min	96.7	70.8	30.6	0	0	0	0	0	0	48.3	118.0	113.4
	max	593.7	567.8	527.5	507.4	464.7	497.7	318.5	309.5	341.5	428.6	498.3	610.4
IWD drip [mm]	min	80.6	59.0	25.5	0	0	0	0	0	0	40.3	98.3	94.5
	max	494.8	473.1	439.6	422.9	387.3	414.7	265.4	257.9	284.6	357.2	415.2	508.6

While the values for the maximum IWD could not be reached in the months without irrigation in the previous two scenarios, this is here the case due to the full irrigation assumption. The minimum of the minimal water demand happens to be from April to June with 55.5 mm each and the maximum with 84.7 mm from July to November. The maximum water demand ranges from 255.8 mm from July to November to 305.6 mm from April to June. For the period between April and September, no irrigation would be necessary to meet the minimum water demand, but with irrigation, the maximum water demand can be met as well. Throughout the rest of the irrigated period from October to March, the minimum of the minimal values lies at 13.8 mm in March and the maximum at 53.1 mm in December. To cover the minimum of the maximal water demand, 139.3 mm would need to be irrigated in August. For the maximum, 228.3 mm would be necessary in April.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in March with 38.2 mm and the maximum of the minimal water demand in November with 147.5 mm respectively. For the maximal water demand, the values are the lowest in August with 386.9 mm and the highest in December with 763.0 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in March with 30.6 mm and the maximum with 113.4 mm in December. The minimum of the maximal IWD occurs with 309.5 mm in August and the maximum in December with 610.4 mm. For drip irrigation, the minimum of the minimal IWD occurs in March with 25.5 mm and the maximum with 94.5 mm in December. The minimum of the maximal IWD occurs with 257.9 mm in August and the maximum in December with 508.6 mm.

Table 50 shows the IWD for the Kola zone for cash crops under full irrigation.

Table 50: IWD for Kola with and without losses for cash crops under full irrigation

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]	779.8	16.2	27.8	45.9	77.2	96.4	81.6	112.5	116.6	102.2	62.9	31.6	8.7
WD [mm]	min	103.3	103.3	66.7	66.7	100.0	100.0	100.0	66.7	66.7	66.7	66.7	100.0
	max	187.8	187.8	253.3	253.3	247.8	247.8	247.8	253.3	253.3	253.3	253.3	247.8
IWD w/o losses [mm]	min	87.2	75.5	20.7	0	3.6	18.4	0	0	0	3.7	35.1	91.3
	max	171.6	159.9	207.4	176.1	151.3	166.2	135.3	136.8	151.2	190.4	211.7	239.1
IWD furrow [mm]	min	242.1	209.7	57.6	0	9.9	51.1	0	0	0	10.3	35.1	91.3
	max	476.7	444.3	576.1	489.2	420.3	461.5	375.7	379.9	419.9	528.9	221.7	239.1
IWD sprinkler [mm]	min	193.7	167.8	46.0	0	7.9	40.9	0	0	0	8.3	77.9	203.0
	max	381.3	355.4	460.9	391.4	336.3	369.2	300.6	304.0	335.9	423.1	492.7	531.3
IWD drip [mm]	min	161.4	139.8	38.4	0	6.6	34.1	0	0	0	6.8	64.9	169.1
	max	317.8	296.2	384.1	326.1	280.2	307.7	250.5	253.3	279.9	352.6	410.6	442.8

The minimum of the minimal water demand happens to be in March and April and from August to November, with 66.7 mm each and the maximum with 103.3 mm in January and February. The maximum water demand ranges from 187.8 mm in January and February to 253.3 mm in March and April and from August to November. In April and for the period between July and September, no irrigation would be necessary to meet the minimum water demand, but with irrigation the maximum water demand can be met as well. Throughout the rest of the irrigated period from October to March and in May and June, the minimum of the minimal values lies at 3.6 mm in May and the maximum at 91.3 mm in December. To cover the minimum of the maximal water demand, 135.3 mm would need to be irrigated in July. For the maximum, 239.1 mm would be necessary in December.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in May with 9.9 mm and the maximum of the minimal water demand in December with 253.7 mm respectively. For the maximal water demand, the values are the lowest in July with 375.7 mm and the highest in December with 664.2 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in May with 7.9 mm and the maximum with 203.0 mm in December. The minimum of the maximal IWD occurs with 300.6 mm in July and the maximum in December with 531.3 mm. For drip irrigation, the minimum of the minimal IWD occurs in May with 6.6 mm and the maximum with 169.1 mm in December. The minimum of the maximal IWD occurs with 250.5 mm in July and the maximum in December with 442.8 mm.

Weynadega

The results of the IWD for the Weynadega zone with a food cropping pattern under supplemental irrigation are displayed in Table 51.

Table 51: IWD for Weynadega with and without losses for food crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1193.0	17.8	32.1	63.8	94.3	124.8	146.2	214.2	216.1	151.2	81.7	36.2	14.3
WD [mm]	min		128.9	128.9	122.2	122.2	103.9	128.9	128.9	128.9	128.9	120.6	120.6	120.6
	max		263.3	263.3	227.8	227.8	166.1	263.3	263.3	263.3	263.3	182.8	182.8	182.8
IWD w/o losses [mm]	min		111.1	96.8	58.4	27.9	0	0	0	0	0	38.9	84.3	106.3
	max		245.6	231.3	164.0	133.4	0	0	0	0	0	101.1	146.5	168.5
IWD furrow [mm]	min		308.7	269.0	162.4	77.5	0	0	0	0	0	108.0	234.3	295.2
	max		682.1	642.4	455.5	370.7	0	0	0	0	0	280.8	407.0	468.0
IWD sprinkler [mm]	min		247.0	215.2	129.9	62.0	0	0	0	0	0	86.4	187.4	236.2
	max		545.7	514.0	364.4	296.5	0	0	0	0	0	224.6	325.6	374.4
IWD drip [mm]	min		205.8	179.3	108.2	51.7	0	0	0	0	0	72.0	156.2	194.8
	max		454.8	428.3	303.7	247.1	0	0	0	0	0	187.2	271.4	312.0

Here, the period in which no irrigation will be done was set from May to September. Since another climate zone is observed now, the precipitation values differ from the previous four tables. This applies for all upcoming Weynadega-related tables. The minimum of the minimal water demand happens to be in May with 103.9 mm and the maximum with 128.9 mm in January and February, and from June to September. The maximum water demand ranges from 166.1 mm in May to 263.3 mm in January and February and from June to September. The months of May to September are not irrigated, as the minimum and maximum water requirement is covered by rain. Throughout the rest of the irrigated period, the minimum of the minimal IWD values lies at 27.9 mm in April and the maximum at 111.1 mm in January. The minimum of the maximal IWD is located in October with 101.1 mm and the maximum lies in January with 245.6 mm.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in April with 77.5 mm and the maximum of the minimal water demand in January with 308.7 mm respectively. For the maximal water demand, the values are the lowest in October with 280.8 mm and the highest in January with 682.1 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in April with 62.9 mm and the maximum with 247.9 mm in January. The minimum of the maximal IWD occurs with 224.4 mm in October and the maximum in January with 545.7 mm. For drip irrigation, the minimum of the minimal IWD occurs in April with 51.7 mm and the maximum with 205.8 mm in January. The minimum of the maximal IWD occurs with 187.2 mm in October and the maximum in January with 454.8 mm.

The results of the IWD for the Weynadega zone with a cash cropping pattern under supplemental irrigation are displayed in Table 52.

Table 52: IWD for Weynadega with and without losses for cash crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1193.0	17.8	32.1	63.8	94.3	124.8	146.2	214.2	216.1	151.2	81.7	36.2	14.3
WD [mm]	min		70.0	70.0	70.0	70.0	70.0	66.7	66.7	66.7	66.7	88.9	88.9	88.9
	max		217.8	217.8	217.8	217.8	217.8	257.0	257.0	257.0	257.0	172.2	172.2	172.2
IWD w/o losses [mm]	min		52.2	37.9	6.2	0	0	0	0	0	0	7.2	52.7	74.7
	max		200.0	185.7	154.0	123.5	0	0	0	0	0	90.5	136.0	157.9
IWD furrow [mm]	min		145.1	105.4	17.3	0	0	0	0	0	0	20.0	146.3	207.3
	max		555.6	516.0	427.8	343.0	0	0	0	0	0	251.5	377.8	438.7
IWD sprinkler [mm]	min		116.1	84.3	13.8	0	0	0	0	0	0	16.0	117.0	165.8
	max		444.5	412.8	342.3	274.4	0	0	0	0	0	201.2	302.2	351.0
IWD drip [mm]	min		96.7	70.3	11.5	0	0	0	0	0	0	13.3	97.5	138.2
	max		370.4	344.0	285.2	228.7	0	0	0	0	0	167.7	251.9	292.5

Here, the period in which no irrigation will be done was set from May to September. The minimum of the minimal water demand happens to be in the period from June to September with 66.7 mm each and the maximum with 88.9 mm from October to December. The maximum water demand ranges from 172.2 mm from October to December to 257.0 mm from July to September. Again, the irrigation water demand cannot be covered by the precipitation except for the minimal water demand in April. To cover the maximal water demand in April, 123.5 mm water has to be irrigated. Throughout the rest of the irrigated period, the minimum of the minimal values lies at 6.2 mm in March and the maximum at 74.7 mm in December. The minimum of the maximal irrigation demand lies in October with 90.5 mm and the maximum lies in January with 200.0 mm.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in March with 17.3 mm and the maximum of the minimal water demand in December with 207.3 mm respectively. For the maximal water demand, the values are the lowest in October with 251.5 mm and the highest in January with 555.6 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in March with 13.8 mm and the maximum with 165.8 mm in December. The minimum of the maximal IWD occurs with 201.2 mm in October and the maximum in January with 444.5 mm. For drip irrigation, the minimum of the minimal IWD occurs in March with 11.5 mm and the maximum with 138.2 mm in December. The minimum of the maximal IWD occurs with 167.7 mm in October and the maximum in January with 370.4 mm.

Table 53 shows the IWD for the Weynadega zone for food crops under full irrigation.

Table 53: IWD for Weynadega with and without losses for food crops under full irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1193.0	17.8	32.1	63.8	94.3	124.8	146.2	214.2	216.1	151.2	81.7	36.2	14.3
WD [mm]	min		137.5	133.3	133.3	91.7	91.7	121.9	126.1	126.1	126.1	109.2	114.2	114.2
	max		227.8	255.6	255.6	352.8	352.8	371.0	364.7	364.7	364.7	306.3	300.0	300.0
IWD w/o losses [mm]	min		119.7	101.3	69.6	0	0	0	0	0	0	27.5	77.9	99.9
	max		210.0	223.5	191.8	258.5	228.0	224.8	150.1	213.5	213.5	224.6	263.8	285.7
IWD furrow [mm]	min		332.6	281.4	193.2	0	0	0	0	0	0	76.3	216.4	277.5
	max		583.3	620.9	532.7	718.0	633.3	624.3	417.1	412.9	593.2	623.8	732.7	793.7
IWD sprinkler [mm]	min		266.1	225.1	154.6	0	0	0	0	0	0	61.1	173.2	222.0
	max		466.7	496.7	426.2	574.4	506.7	499.4	333.7	330.4	474.5	499.0	586.2	639.9
IWD drip [mm]	min		221.7	187.6	128.8	0	0	0	0	0	0	50.9	144.3	185.0
	max		388.9	413.9	355.1	478.7	422.2	416.2	278.0	275.3	395.4	415.8	488.5	529.1

While the values for the maximum IWD could not be reached in the months without irrigation in the previous two scenarios, it is here the case due to the full irrigation assumption. The minimum of the minimal water demand happens to be in April and May with 91.7 mm each and the maximum with 137.5 mm in January. The maximum water demand ranges from 227.8 mm in January to 354.7 mm from July to September. For the period between April and September, no irrigation would be necessary to meet the minimum water demand, but with irrigation the maximum water demand can be met as well. Throughout the rest of the irrigated period from October to March, the minimum of the minimal values lies at 27.5 mm in October and the maximum at 119.7 mm in January. To cover the minimum of the maximal water demand, 150.1 mm would need to be irrigated in July. For the maximum, 285.7 mm would be necessary in December.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in October with 76.3 mm and the maximum of the minimal water demand in January with 332.6 mm respectively. For the maximal water demand, the values are the lowest in August with 412.9 mm and the highest in December with 793.7 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in October with 61.1 mm and the maximum with 266.1 mm in January. The minimum of the maximal IWD occurs with 330.4 mm in August and the maximum in December with 639.9 mm. For drip irrigation, the minimum of the minimal IWD occurs in October with 50.9 mm and the maximum with 221.7 mm in January. The minimum of the maximal IWD occurs with 275.3 mm in August and the maximum in December with 529.1 mm.

Table 54 shows the IWD for the Weynadega zone for cash crops under full irrigation.

Table 54: IWD for Weynadega with and without losses for cash crops under full irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1193.0	17.8	32.1	63.8	94.3	124.8	146.2	214.2	216.1	151.2	81.7	36.2	14.3
WD [mm]	min		58.9	58.9	58.9	58.9	58.9	55.6	55.6	55.6	55.6	77.8	77.8	77.8
	max		195.6	195.6	195.6	195.6	195.6	234.7	234.7	234.7	234.7	150.0	150.0	150.0
IWD w/o losses [mm]	min		41.1	26.8	0	0	0	0	0	0	0	0	41.6	63.5
	max		177.8	163.5	131.8	101.2	70.8	88.5	20.1	18.7	83.5	68.3	113.8	135.7
IWD furrow [mm]	min		114.3	74.6	0	0	0	0	0	0	0	0	115.5	176.4
	max		493.9	454.2	366.1	281.2	196.6	245.8	56.0	51.8	232.0	189.7	316.0	377.0
IWD sprinkler [mm]	min		91.4	59.7	0	0	0	0	0	0	0	0	92.4	141.1
	max		395.1	363.4	292.8	225.0	157.3	196.7	44.8	41.5	185.6	151.8	252.8	301.6
IWD drip [mm]	min		76.2	49.7	0	0	0	0	0	0	0	0	77.0	117.6
	max		329.3	302.8	244.0	187.6	131.0	163.9	37.3	34.6	154.7	126.5	210.7	251.3

The minimum of the minimal water demand happens to be from June to September with 55.6 mm each and the maximum with 77.8 mm from October to December in. The maximum water demand ranges from 150.0 mm from October to December to 234.7 mm from June to September. For the period between March and October, no irrigation would be necessary to meet the minimum water demand, but with irrigation, the maximum water demand can be met as well. Throughout the rest of the irrigated period from November to February, the minimum of the minimal values lies at 26.8 mm in February and the maximum at 63.5 mm in December. To cover the minimum of the maximal water demand, 18.7 mm would need to be irrigation in August. For the maximum, 177.8 mm would be necessary in January.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in February with 74.6 mm and the maximum of the minimal water demand in December with 176.4 mm respectively. For the maximal water demand, the values are the lowest in August with 51.8 mm and the highest in January with 493.9 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in February with 59.7 mm and the maximum with 141.1 mm in December. The minimum of the maximal IWD occurs with 41.5 mm in August and the maximum in January with 395.1 mm. For drip irrigation, the minimum of the minimal IWD occurs in February with 49.7 mm and the maximum with 117.6 mm in December. The minimum of the maximal IWD occurs with 34.6 mm in August and the maximum in January with 329.3 mm.

Dega

The results of the IWD for the Dega zone with a food cropping pattern under supplemental irrigation are displayed in Table 55.

Table 55: IWD for Dega with and without losses for food crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1135.0	25.6	41.3	74.8	102.9	100.0	105.4	206.7	203.8	132.1	83.1	39.4	20.0
WD [mm]	min	40.8	40.8	40.8	40.8	46.4	46.4	46.4	49.2	40.8	59.7	59.7	38.1	
	max	203.3	203.3	203.3	203.3	264.4	264.4	264.4	211.7	203.3	294.4	294.4	256.1	
IWD w/o losses [mm]	min	15.3	0	0	0	0	0	0	0	0	0	20.3	18.1	
	max	177.8	162.0	128.6	100.5	0	0	0	0	0	0	255.0	236.1	
IWD furrow [mm]	min	42.4	0	0	0	0	0	0	0	0	0	56.5	50.3	
	max	493.8	450.0	357.1	279.1	0	0	0	0	0	0	708.5	656.0	
IWD sprinkler [mm]	min	33.9	0	0	0	0	0	0	0	0	0	45.2	40.2	
	max	395.0	360.0	285.7	223.3	0	0	0	0	0	0	566.8	524.8	
IWD drip [mm]	min	28.3	0	0	0	0	0	0	0	0	0	37.7	33.5	
	max	329.2	300.0	238.1	186.0	0	0	0	0	0	0	472.3	437.3	

Here, the period in which no irrigation will be done was set from May to September. Since another climate zone is observed now, the precipitation values differ from the previous four tables. This applies for all upcoming Dega-related tables. The minimum of the minimal water demand happens to be from January to April and in September with 40.8 mm each and the maximum with 59.7 mm in October and November. The maximum water demand ranges from 203.3 mm from January to April to 294.4 mm in October and November. For the period between March and October, no irrigation would be necessary to meet the minimum water demand, but with irrigation the maximum water demand can be met as well. Throughout the rest of the irrigated period from November to January, the minimum of the minimal values lies at 15.8 mm in January and the maximum at 20.3 mm in November. To cover the minimum of the maximal water demand, 100.5 mm would need to be irrigation in April. For the maximum, 255.0 mm would be necessary in November.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in January with 42.4 mm and the maximum of the minimal water demand in November with 56.5 mm respectively. For the maximal water demand, the values are the lowest in April with 279.1 mm and the highest in November with 708.5 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in January with 33.9 mm and the maximum with 566.8 mm in November. The minimum of the maximal IWD occurs with 223.3 mm in April and the maximum in November with 566.8 mm. For drip irrigation, the minimum of the minimal IWD occurs in January with 28.3 mm and the maximum with 37.7 mm in November. The minimum of the maximal IWD occurs with 186.0 mm in April and the maximum in November with 472.3 mm.

The results of the IWD for the Dega zone with a cash cropping pattern under supplemental irrigation are displayed in Table 56.

Table 56: IWD for Dega with and without losses for cash crops under supplemental irrigation

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]	1135.0	25.6	41.3	74.8	102.9	100.0	105.4	206.7	203.8	132.1	83.1	39.4	20.0
WD [mm]	min	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max	258.3	258.3	258.3	258.3	337.5	337.5	337.5	337.5	245.8	245.8	245.8	245.8
IWD w/o losses [mm]	min	21.7	5.9	0	0	0	0	0	0	0	0	7.8	27.3
	max	232.8	217.0	183.6	155.5	0	0	0	0	0	0	206.4	225.9
IWD furrow [mm]	min	60.2	16.3	0	0	0	0	0	0	0	0	21.8	75.8
	max	646.6	602.7	509.9	431.8	0	0	0	0	0	0	573.5	627.0
IWD sprinkler [mm]	min	48.2	13.1	0	0	0	0	0	0	0	0	17.4	60.6
	max	517.3	482.2	407.9	345.5	0	0	0	0	0	0	458.8	501.9
IWD drip [mm]	min	40.1	10.9	0	0	0	0	0	0	0	0	14.5	50.5
	max	431.1	401.8	339.9	287.9	0	0	0	0	0	0	382.3	418.3

Here, the period in which no irrigation will be done was set from May to October. The minimal water demand is assumed to be constant at 47.2 mm every month. The maximum water demand ranges from 245.8 mm from September to December to 337.5 mm from May to August. Again, the irrigation water demand cannot be covered by the precipitation except for the minimal water demand in March and April. To cover the maximal water demand in March, 183.6 mm and in April, 155.5 mm water has to be irrigated. Throughout the rest of the irrigated period, the minimum of the minimal values lies at 5.9 mm in February and the maximum at 27.3 mm in December. The minimum of the maximal irrigation demand lies in April with 155.5 mm and the maximum lies in January with 232.8 mm.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in February with 16.3 mm and the maximum of the minimal water demand in December with 75.8 mm respectively. For the maximal water demand, the values are the lowest in April with 431.8 mm and the highest in January with 646.6 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in February with 13.1 mm and the maximum with 60.6 mm in December. The minimum of the maximal IWD occurs with 345.5 mm in April and the maximum in January with 517.3 mm. For drip irrigation, the minimum of the minimal IWD occurs in February with 10.9 mm and the maximum with 50.5 mm in December. The minimum of the maximal IWD occurs with 287.9 mm in April and the maximum in January with 418.3 mm.

Table 57 shows the IWD for the Dega zone for food crops under full irrigation.

Table 57: IWD for Dega with and without losses for food crops under full irrigation

	An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]	1135.0	25.6	41.3	74.8	102.9	100.0	105.4	206.7	203.8	132.1	83.1	39.4	20.0
WD [mm]	min	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3
	max	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7	316.7
IWD w/o losses [mm]	min	32.8	17.0	0	0	0	0	0	0	0	0	18.9	38.4
	max	291.1	275.3	241.9	213.8	216.7	211.3	109.9	122.9	184.6	233.6	277.3	296.7
IWD furrow [mm]	min	91.0	47.2	0	0	0	0	0	0	0	0	52.6	106.6
	max	808.6	764.8	671.9	593.9	602.0	586.9	305.4	313.6	512.7	648.8	770.2	824.2
IWD sprinkler [mm]	min	72.8	37.7	0	0	0	0	0	0	0	0	42.1	85.3
	max	646.9	611.8	537.5	475.1	481.6	469.5	244.3	250.9	410.2	519.1	616.2	659.4
IWD drip [mm]	min	60.7	31.5	0	0	0	0	0	0	0	0	35.1	71.1
	max	539.1	509.8	447.9	395.9	401.3	391.3	203.6	209.0	341.8	432.6	513.5	549.5

While the values for the maximum IWD could not be reached in the months without irrigation in the previous two scenarios, it is here the case due to the full irrigation assumption. The minimal water demand is assumed to be constant at 58.3 mm every month, just as the maximal water demand, assumed to be 316.7 mm every month. For the period between March and October, no irrigation would be necessary to meet the minimum water demand, but with irrigation the maximum water demand can be met as well. Throughout the rest of the irrigated period from November to February, the minimum of the minimal values lies at 17.0 mm in February and the maximum at 38.4 mm in December. To cover the minimum of the maximal water demand, 109.9 mm would need to be irrigated in July. For the maximum, 296.7 mm would be necessary in December.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in February with 47.2 mm and the maximum of the minimal water demand in December with 106.6 mm respectively. For the maximal water demand, the values are the lowest in July with 305.4 mm and the highest in December with 824.2 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in February with 37.7 mm and the maximum with 85.3 mm in December. The minimum of the maximal IWD occurs with 244.3 mm in July and the maximum in December with 659.4 mm. For drip irrigation, the minimum of the minimal IWD occurs in February with 31.5 mm and the maximum with 71.1 mm in December. The minimum of the maximal IWD occurs with 203.6 mm in July and the maximum in December with 549.5 mm.

Table 58 shows the IWD for the Dega zone for cash crops under full irrigation

Table 58: IWD for Dega with and without losses for cash crops under full irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1135.0	25.6	41.3	74.8	102.9	100.0	105.4	206.7	203.8	132.1	83.1	39.4	20.0
WD [mm]	min	43.9	43.9	43.9	43.9	77.2	77.2	77.2	43.9	43.9	80.6	80.6	77.2	
	max	308.3	308.3	308.3	308.3	211.1	211.1	211.1	216.7	216.7	161.1	161.1	211.1	
IWD w/o losses [mm]	min	18.3	2.6	0	0	0	0	0	0	0	0	41.2	57.3	
	max	282.8	267.0	233.6	205.5	111.1	105.7	4.4	12.9	84.6	78.0	121.7	191.1	
IWD furrow [mm]	min	50.9	7.1	0	0	0	0	0	0	0	0	114.4	159.1	
	max	785.5	741.6	648.8	570.7	308.7	293.6	12.1	35.8	234.9	216.7	338.1	531.0	
IWD sprinkler [mm]	min	40.7	5.7	0	0	0	0	0	0	0	0	91.5	127.3	
	max	628.0	593.3	519.0	456.6	247.0	234.9	9.7	28.6	188.0	173.4	270.5	424.8	
IWD drip [mm]	min	34.0	4.7	0	0	0	0	0	0	0	0	76.3	106.1	
	max	523.6	494.4	432.5	380.5	205.8	195.8	8.1	23.9	156.6	144.5	255.4	354.0	

The minimum of the minimal water demand happens to be from January to April with 43.9 mm each and the maximum with 80.6 mm in October and November. The maximum water demand ranges from 161.1 mm in October and November to 308.3 mm from January to April. For the period between March and October, no irrigation would be necessary to meet the minimum water demand, but with irrigation the maximum water demand can be met as well. Throughout the rest of the irrigated period from November to February, the minimum of the minimal values lies at 2.6 mm in February and the maximum at 191.1 mm in December. To cover the minimum of the maximal water demand, 4.4 mm would need to be irrigated in July. For the maximum, 282.8 mm would be necessary in January.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in February with 7.1 mm and the maximum of the minimal water demand in December with 159.1 mm respectively. For the maximal water demand, the values are the lowest in July with 12.1 mm and the highest in January with 785.5 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in February with 5.7 mm and the maximum with 127.3 mm in December. The minimum of the maximal IWD occurs with 9.7 mm in July and the maximum in January with 628.0 mm. For drip irrigation, the minimum of the minimal IWD occurs in February with 4.7 mm and the maximum with 106.1 mm in December. The minimum of the maximal IWD occurs with 8.1 mm in July and the maximum in January with 523.6 mm.

Wurich

As mentioned before, the diversity of the crops selected for the Wurich zone is low due to the climatic conditions. Hence, the two respective sets of results for food crops and cash crops only are differing regarding the irrigation type (supplemental for full irrigation). The results of the IWD for the Wurich zone with a food cropping pattern under supplemental irrigation are displayed in Table 59.

Table 59: IWD for Wurich with and without losses for food crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1063.2	16.0	24.6	61.8	68.8	104.0	114.4	326.4	347.8	134.2	56.4	27.4	11.6
WD [mm]	min	62.5	62.5	59.7	59.7	59.7	59.7	45.8	45.8	45.8	45.8	62.5	62.5
	max	250.0	250.0	294.4	294.4	294.4	294.4	416.7	416.7	416.7	416.7	250.0	250.0
IWD w/o losses [mm]	min	46.5	37.9	0	0	0	0	0	0	0	0	35.1	50.9
	max	234.9	255.4	232.6	255.6	0	0	0	0	0	0	222.6	238.4
IWD furrow [mm]	min	128.2	105.3	0	0	0	0	0	0	0	0	97.5	141.4
	max	650.0	525.1	646.2	626.8	0	0	0	0	0	0	618.3	662.2
IWD sprinkler [mm]	min	103.3	84.2	0	0	0	0	0	0	0	0	78.0	113.1
	max	520.0	500.9	517.0	501.4	0	0	0	0	0	0	494.7	529.8
IWD drip [mm]	min	86.1	70.2	0	0	0	0	0	0	0	0	65.0	94.3
	max	433.3	417.4	430.8	417.8	0	0	0	0	0	0	412.2	441.5

The minimum of the minimal water demand happens to be from July to October with 45.8 mm each and the maximum with 62.5 mm from November to February. The maximum water demand ranges from 250.0 mm from November to February to 416.7 mm from July to October. The months May to October are left unirrigated as the minimum water demand is covered by rainfall. In addition, no irrigation is required to cover the minimum demand in March and April, but irrigation is performed, nonetheless. 232.6 mm and 225.6 mm would be needed to be irrigated in these two months. Throughout the rest of the irrigated period from November to February, the minimum of the minimal values lies at 35.1 mm in November and the maximum at 50.9 mm in December. To cover the minimum of the maximal water demand, 222.6 mm would need to be irrigated in November. For the maximum, 255.6 mm would be necessary in April.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in November with 97.5 mm and the maximum of the minimal water demand in December with 141.1 mm respectively. For the maximal water demand, the values are the lowest in November with 618.3 mm and the highest in December with 662.2 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in November with 78.0 mm and the maximum with 113.1 mm in December. The minimum of the maximal IWD occurs with 494.7 mm in November and the maximum in December with 529.8 mm. For drip irrigation, the minimum of the minimal IWD occurs in November with 65.0 mm and the maximum with 94.3 mm in December. The minimum of the maximal IWD occurs with 412.2 mm in November and the maximum in December with 441.5 mm.

The results of the IWD for the Wurich zone with a cash cropping pattern under supplemental irrigation are displayed in Table 60.

Table 60: IWD for Wurich with and without losses for cash crops under supplemental irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1063.2	16.0	24.6	61.8	68.8	104.0	114.4	326.4	347.8	134.2	56.4	27.4	11.6
WD [mm]	min	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0
IWD w/o losses [mm]	min	31.2	22.6	0	0	0	0	0	0	0	0	0	19.8	35.6
	max	309.0	300.4	263.2	256.2	0	0	0	0	0	0	268.6	297.6	313.4
IWD furrow [mm]	min	86.8	62.9	0	0	0	0	0	0	0	0	0	55.1	99.0
	max	858.3	834.4	741.1	711.7	0	0	0	0	0	0	746.1	826.7	870.6
IWD sprinkler [mm]	min	69.4	50.3	0	0	0	0	0	0	0	0	0	44.1	79.2
	max	686.7	667.6	584.9	569.3	0	0	0	0	0	0	596.9	661.3	696.4
IWD drip [mm]	min	57.8	41.9	0	0	0	0	0	0	0	0	0	36.7	66.0
	max	572.2	556.3	487.4	474.0	0	0	0	0	0	0	497.4	551.1	580.4

The minimal and maximal water demand are assumed to be constant at 47.2 mm and 325.0 mm every month. For the chosen crops in the developed pattern, no irrigation needs to be done in the month from May to September as the precipitation covers the water demand of the plants. In July and August, the precipitation even exceeds the maximal limit of the crops' water demand. This, however, was assumed to not be harming for the crops as mentioned in chapter 6.3.1. The minimal water demand for March, April, and October is also covered by the precipitation, so no additional irrigation is needed here. The maxima of the maximal irrigation water demand are 256.2 mm in April, 263.2 mm in March and 268.2 mm in October. In the remaining irrigation period from November to February, the minimal values range from 19.8 mm in November to 35.6 mm in December and the maximal values range from 297.6 mm in November to 313.4 mm in December.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in November with 55.1 mm and the maximum of the minimal water demand in December with 99.0 mm respectively. For the maximal water demand, the values are the lowest in November with 826.7 mm and the highest in December with 870.6 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in November with 44.1 mm and the maximum with 79.2 mm in December. The minimum of the maximal IWD occurs with 661.3 mm in November and the maximum in December with 696.4 mm. For drip irrigation, the minimum of the minimal IWD occurs in November with 36.7 mm and the maximum with 66.0 mm in December. The minimum of the maximal IWD occurs with 551.1 mm in November and the maximum in December with 580.4 mm.

Table 61 shows the IWD for the Wurich zone for food crops under full irrigation and Table 62 shows the IWD for the Wurich zone for cash crops under full irrigation.

Table 61: IWD for Wurich with and without losses for food crops under full irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1063.2	16.0	24.6	61.8	68.8	104.0	114.4	326.4	347.8	134.2	56.4	27.4	11.6
WD [mm]	min	62.5	62.5	59.7	59.7	59.7	59.7	45.8	45.8	45.8	45.8	62.5	62.5	
	max	250.0	250.0	294.4	294.4	294.4	294.4	416.7	416.7	416.7	416.7	250.0	250.0	
IWD w/o losses [mm]	min	46.5	37.9	0	0	0	0	0	0	0	0	35.1	50.9	
	max	234.0	255.4	232.6	225.6	190.4	180.0	90.3	68.9	282.5	360.3	222.6	238.4	
IWD furrow [mm]	min	129.2	105.3	0	0	0	0	0	0	0	0	97.5	141.4	
	max	650.0	626.1	646.2	626.8	529.0	500.1	250.7	191.3	784.6	1000.7	618.3	662.2	
IWD sprinkler [mm]	min	103.3	84.2	0	0	0	0	0	0	0	0	78.0	113.1	
	max	520.0	500.9	517.0	501.4	423.2	400.1	200.6	153.0	627.7	800.6	494.7	529.8	
IWD drip [mm]	min	86.1	70.2	0	0	0	0	0	0	0	0	65.0	94.3	
	max	433.3	417.4	430.8	417.8	352.7	333.4	167.2	127.5	523.1	667.2	412.2	441.5	

Table 62: IWD for Wurich with and without losses for cash crops under full irrigation

		An	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
av. precip. [mm]		1063.2	16.0	24.6	61.8	68.8	104.0	114.4	326.4	347.8	134.2	56.4	27.4	11.6
WD [mm]	min		47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2
	max		325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0	325.0
IWD w/o losses [mm]	min		31.2	22.6	0	0	0	0	0	0	0	0	19.8	35.6
	max		309.0	300.4	263.2	256.2	221.0	210.6	0	0	190.8	268.6	297.6	313.4
IWD furrow [mm]	min		86.8	62.9	0	0	0	0	0	0	0	0	55.1	99.0
	max		858.3	834.4	731.1	711.7	613.9	585.0	0	0	530.0	746.1	826.7	870.6
IWD sprinkler [mm]	min		69.4	50.3	0	0	0	0	0	0	0	0	44.1	79.2
	max		686.7	667.6	584.9	569.3	491.1	468.0	0	0	424.0	596.9	661.3	696.4
IWD drip [mm]	min		57.8	41.9	0	0	0	0	0	0	0	0	36.7	66.0
	max		572.2	556.3	487.4	474.4	409.3	390.0	0	0	353.3	497.4	551.1	580.4

The only difference between these two tables is the months in which irrigation is not applied in the supplemental irrigation scenarios and in which month of the full irrigation scenario, in which additional water is applied to reach the maximal water demand of the plants. In Table 61, for the months from May to October, supplemental irrigation is applied. The range of irrigation water demand to cover the maximum water demand in this period is between 68.9 mm in August to 360.3 mm in October.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in November with 97.5 mm and the maximum of the minimal water demand in December with 141.4 mm respectively. For the maximal water demand, the values are the lowest in November with 618.3 mm and the highest in December with 662.2 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in November with 78.0 mm and the maximum with 113.1 mm in December. The minimum of the maximal IWD occurs with 494.7 mm in November and the maximum in December with 529.8 mm. For drip irrigation, the minimum of the minimal IWD occurs in November with 65.0 mm and the maximum with 94.3 mm in December. The minimum of the maximal IWD occurs with 412.2 mm in November and the maximum in December with 441.5 mm.

In Table 62, the months from May to September are left unirrigated in the supplementary scenario. The minimum of the maximal water demand ranges from 190.8 mm in August to 221.0 mm in May. In July and August, again the maximum water demand of the plants is exceeded by the precipitation with no negative effects as assumed.

Including the irrigation and conveyance efficiencies, i.e., the losses, for furrow irrigation, the minimum of the additional minimal water demand occurs in November with 55.1 mm and the maximum of the minimal water demand in December with 99.0 mm respectively. For the maximal water demand, the values are the lowest in November with 826.7 mm and the highest in December with 870.6 mm. For the sprinkler irrigation, the minimum of the minimal IWD occurs in November with 44.1 mm and the maximum with 79.2 mm in December. The minimum of the maximal IWD occurs with 661.3 mm in November and the maximum in December with 696.4 mm. For drip irrigation, the minimum of the minimal IWD occurs in November with 36.7 mm and the maximum with 66.0 mm in December. The minimum of the maximal IWD occurs with 551.1 mm in November and the maximum in December with 580.4 mm.

For the following calculation of the oIWD per climate zone, an overview of the previously calculated monthly IWD values is displayed in Table 63. A numerical labelling was done to simplify further references to the different scenarios during the discussion.

Table 63: Application scenarios and their corresponding oIWD values

	Application Scenarios				IWD per area [mm]		Overall IWD [BCM]	
No	Climate Zone	Irrigation Scenario	Crop type	Irrigation Method	Min	Max	Min	Max
1	CZ1	SI	CP1	IM 1	162.5	3848.6	2.5	59.19
2	CZ1	SI	CP1	IM 2	130.0	3078.9	2.0	47.35
3	CZ1	SI	CP1	IM 3	108.3	2565.8	1.67	39.46
4	CZ1	SI	CP2	IM 1	529.3	4414.1	8.14	67.89
5	CZ1	SI	CP2	IM 2	423.4	3531.3	6.51	54.31
6	CZ1	SI	CP2	IM 3	352.9	2942.8	5.43	45.26
7	CZ1	I	CP1	IM 1	597.3	7082	9.19	108.92
8	CZ1	I	CP1	IM 2	477.9	5665.6	7.35	87.14
9	CZ1	I	CP1	IM 3	398.2	4721.4	6.12	72.62
10	CZ1	I	CP2	IM 1	931.8	5852.6	14.33	90.01
11	CZ1	I	CP2	IM 2	745.4	4682.1	11.46	72.01
12	CZ1	I	CP2	IM 3	621.2	3901.7	9.55	60.01
13	CZ2	SI	CP1	IM 1	1455.1	3306.5	67.85	154.19
14	CZ2	SI	CP1	IM 2	1164.1	2645.2	54.28	123.35
15	CZ2	SI	CP1	IM 3	970	2204.4	45.23	102.79
16	CZ2	SI	CP2	IM 1	641.3	2910.4	29.90	135.72
17	CZ2	SI	CP2	IM 2	513.1	2328.3	23.93	108.57
18	CZ2	SI	CP2	IM 3	427.6	1940.3	19.94	90.48
19	CZ2	I	CP1	IM 1	1377.5	7285.8	64.24	339.75
20	CZ2	I	CP1	IM 2	1102	5828.7	51.39	271.80
21	CZ2	I	CP1	IM 3	918.3	4857.2	42.82	226.50
22	CZ2	I	CP2	IM 1	480.7	3260.4	22.42	152.04
23	CZ2	I	CP2	IM 2	384.6	2608.3	17.93	121.63
24	CZ2	I	CP2	IM 3	320.5	2173.6	14.95	101.36
25	CZ3	SI	CP1	IM 1	149.2	2944.3	4.72	93.20
26	CZ3	SI	CP1	IM 2	119.4	2355.5	3.78	74.56
27	CZ3	SI	CP1	IM 3	99.5	1962.9	3.15	62.13
28	CZ3	SI	CP2	IM 1	174.1	3391.9	5.51	107.37
29	CZ3	SI	CP2	IM 2	139.3	2713.5	4.41	85.89
30	CZ3	SI	CP2	IM 3	116.1	2261.3	3.68	71.58
31	CZ3	I	CP1	IM 1	297.4	7402.9	9.41	234.33
32	CZ3	I	CP1	IM 2	237.9	5922.3	7.53	187.46
33	CZ3	I	CP1	IM 3	198.3	4935.3	6.28	156.22
34	CZ3	I	CP2	IM 1	331.5	4717.5	10.49	149.33
35	CZ3	I	CP2	IM 2	265.2	3774	8.39	119.46
36	CZ3	I	CP2	IM 3	221	3145	7.00	99.55
37	CZ4	SI	CP1	IM 1	473.3	3829.6	0.46	3.73
38	CZ4	SI	CP1	IM 2	378.7	3063.7	0.37	2.99
39	CZ4	SI	CP1	IM 3	315.6	2553.1	0.31	2.49
40	CZ4	SI	CP2	IM 1	303.7	5578.9	0.30	5.44
41	CZ4	SI	CP2	IM 2	243	4463.1	0.24	4.35
42	CZ4	SI	CP2	IM 3	202.5	3719.3	0.20	3.63
43	CZ4	I	CP1	IM 1	473.3	6438	0.46	6.28
44	CZ4	I	CP1	IM 2	378.7	5150.4	0.37	5.02
45	CZ4	I	CP1	IM 3	315.6	4292	0.31	4.18
46	CZ4	I	CP2	IM 1	303.7	7307.8	0.30	7.12
47	CZ4	I	CP2	IM 2	243	5846.2	0.24	5.70
48	CZ4	I	CP2	IM 3	202.5	4871.9	0.20	4.75

Since the plain numerical labelling might be confusing, another, more comprehensible "code" was introduced to clearly identify the properties of a specific scenario. In the column "Climate zone" CZ1 stands for Kola, CZ2 for Weynadega, CZ3 for Dega and CZ4 for Wurich.

In the column "Irrigation scenario" it is distinguished between "SI" for Supplemental irrigation" and "I" for full irrigation. In the column "Crop type" it is distinguished between "CP1" for the cash crop patterns and "CP2" for the food crop patterns. In the column "Irrigation Method" the three considered techniques IM1 for furrow irrigation, IM2 for sprinkler irrigation and IM3 for drip irrigation are indicated. Having these short labels, it is easier to indicate the properties of a scenario without having to write out each property. For example, the scenario in the Kola zone (CZ1) under full irrigation (I) cultivating food crops (CP1) with furrow irrigation (IM1) can be described in short as scenario CZ1-I-CP1-IM1.

For a more accessible comparability of the results for the different application scenarios within a climate zone, the results are also presented in diagrams below. The diagrams are designed to compare the minimum and the maximum oIWD for each application scenario and each climate zone. The y-axis of the diagrams shows the overall irrigation water demand (oIWD) in BCM. It should be noted that the scale of oIWD varies in the charts to ensure that each set of results is presented in sufficient detail and clarity. This approach makes it possible to visualize the nuances and differences between relatively close values that might be lost with a uniform scale. The x-axis lists the oIWD for all application scenarios to allow for an easy comparison across the different scenarios.

In Figure 31 the oIWDs for the Kola zone (CZ1) are shown. The oIWD is between 1.67 BCM for scenario SI-CP1-IM3 and 59.19 BCM for scenario I-CP1-IM1. The minimum oIWDs correspond to between 4.2% and 15.9% of the maximum oIWDs. When comparing those scenarios that differ only in the irrigation method, i.e. SI or I, it is noticeable that for the minimum as well as the maximum oIWD the I-scenarios have higher water demands than the SI-scenarios. For the SI-scenarios the CP2 shows higher minimum and maximum oIWDs than CP1. For the I-scenarios the CP2-scenarios show higher minimum oIWDs, but the CP1-scenarios show higher maximum oIWDs. For each set of scenarios (SI-CP1-IM1/2/3; SI-CP2-IM1/2/3; ...) IM1 (furrow irrigation) has the highest minimum and maximum oIWD.

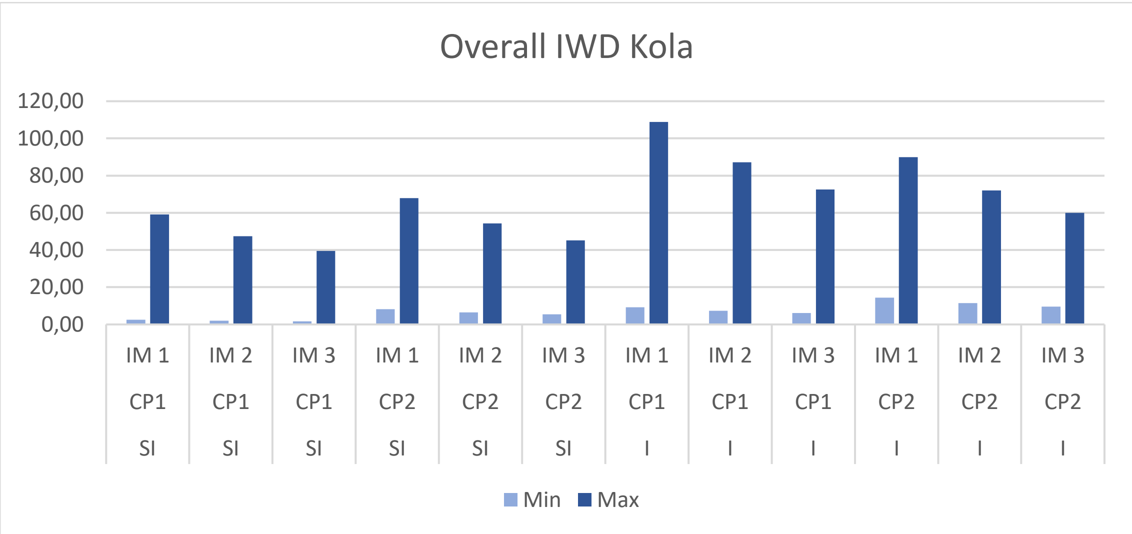

Figure 31: Overall Irrigation Water Demand for the Kola Zone

In Figure 32 the oIWDs for the Weynadega (CZ2) zone are shown. The minimum oIWD is between 14.95 BCM for scenario I-CP2-IM3 and 67.85 BCM for scenario SI-CP1-IM1. The maximum oIWD is between 90.48 BCM for scenario SI-CP2-IM3 and 339.75 BCM for scenario I-CP1-IM1. The minimum oIWDs correspond to between 14.8% and 44.4% of the maximum oIWDs. A comparison of the I- and SI- (full and supplemental irrigation) scenarios shows that for the minimum oIWD the SI-scenarios always show higher demands than the

I-scenarios. For the maximum oIWD, the I-scenarios show higher oIWDs. A comparison of the CP-scenarios within the respective irrigation method shows that CP1 (food crops) has the greater demands for both the SI-scenarios and the I-scenarios. Again, for each set of scenarios (SI-CP1-IM1/2/3; SI-CP2-IM1/2/3; ...) IM1 (furrow irrigation) has the highest minimum and maximum oIWD.

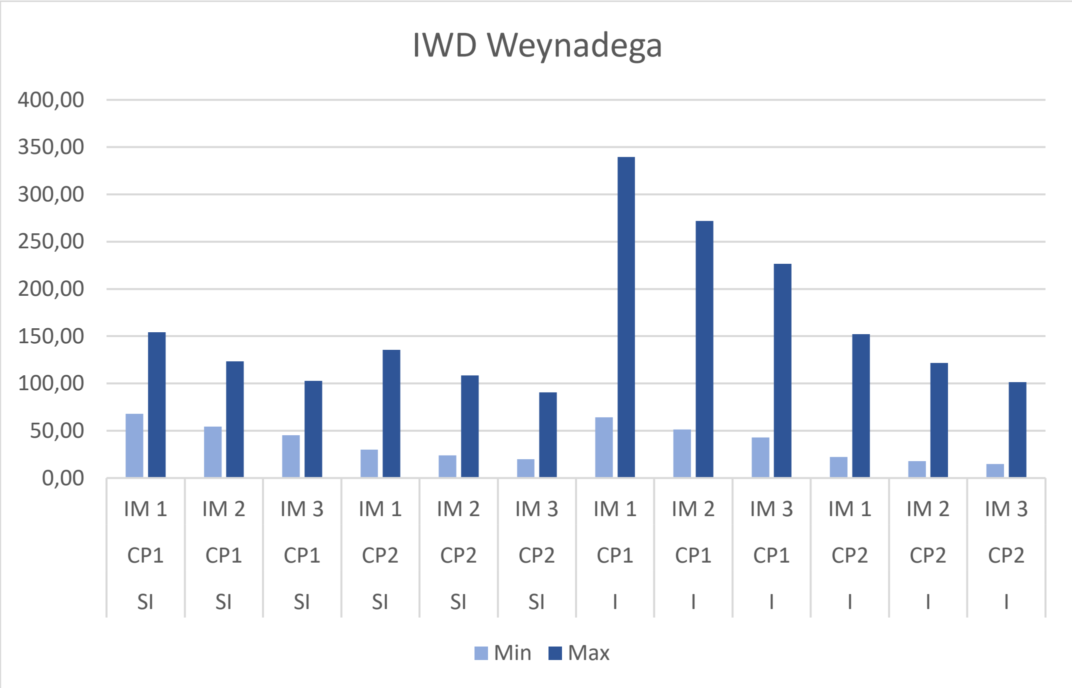

Figure 32: Overall Irrigation Water Demand for the Weynadega Zone

In Figure 33 the oIWDs for the Dega (CZ3) zone are shown. The minimum oIWD is between 3.15 BCM in scenario SI-CP1-IM3 and 10.49 BCM for scenario SI-CP2-IM1. The maximum oIWD is between 62.13 BCM for scenario SI-CP1-IM3 and 234.33 BCM in scenario I-CP1-IM1. The minimum oIWDs correspond to between 4% and 7% of the maximum oIWDs. All I-scenarios show higher oIWDs than the respective SI-scenarios. For the SI-scenarios the CP2-scenarios show higher minimum and maximum oIWDs. For the I-scenarios the CP2-scenarios show higher values the minimum oIWDs, but the CP1-scenarios show higher maximum oIWDs. For each combination of SI & I and CP1 & CP2 IM1 shows the highest values for minimum and maximum oIWD.

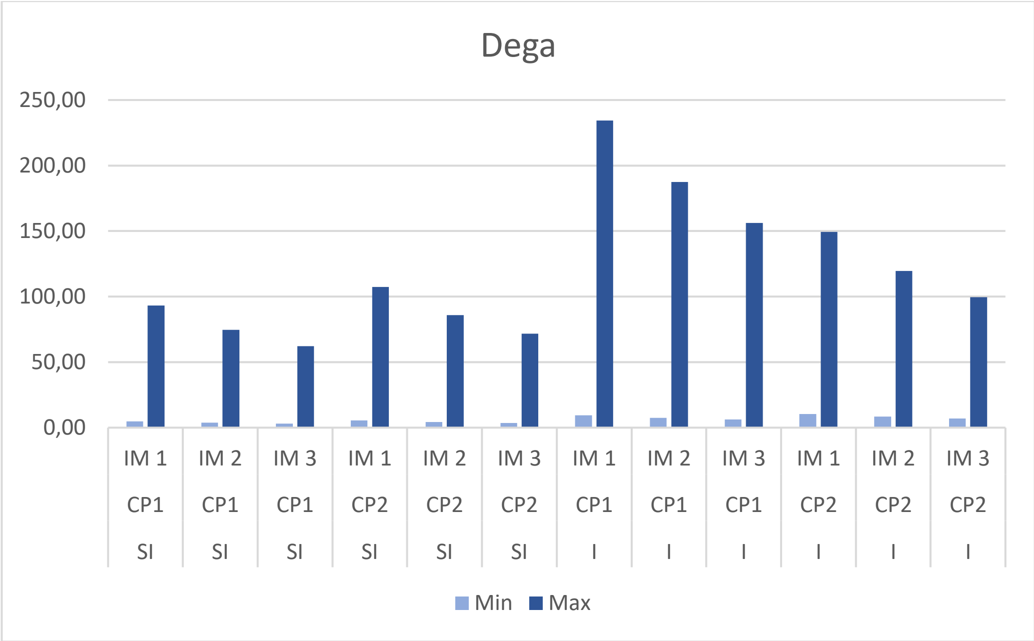

Figure 33: Overall Irrigation Water Demand for the Dega Zone

In Figure 34 the oIWDs for the Wurich zone (CZ4) are shown. The minimum oIWD is between 0.2 BCM for the scenarios SI-CP2-IM3 & I-CP2-3 and 0.5 BCM for the scenarios SI-CP1-IM1 & I-CP1-IM1. The maximum oIWD is between 2.5 BCM for scenario SI-CP1-IM3 and 7.12 BCM in scenario I-CP2-IM1. The minimum oIWDs correspond to between 4.2% and 12.4% of the maximum oIWDs. The I-scenarios show higher oIWD values for all CP-IM-scenarios than the SI-scenarios. For the minimum oIWD of the SI-scenarios and the I-scenarios the CP1-scenarios show higher results. For the maximum oIWD of both irrigation scenarios the CP2-scenarios show higher results. The IM1-scenarios show always the highest oIWD.

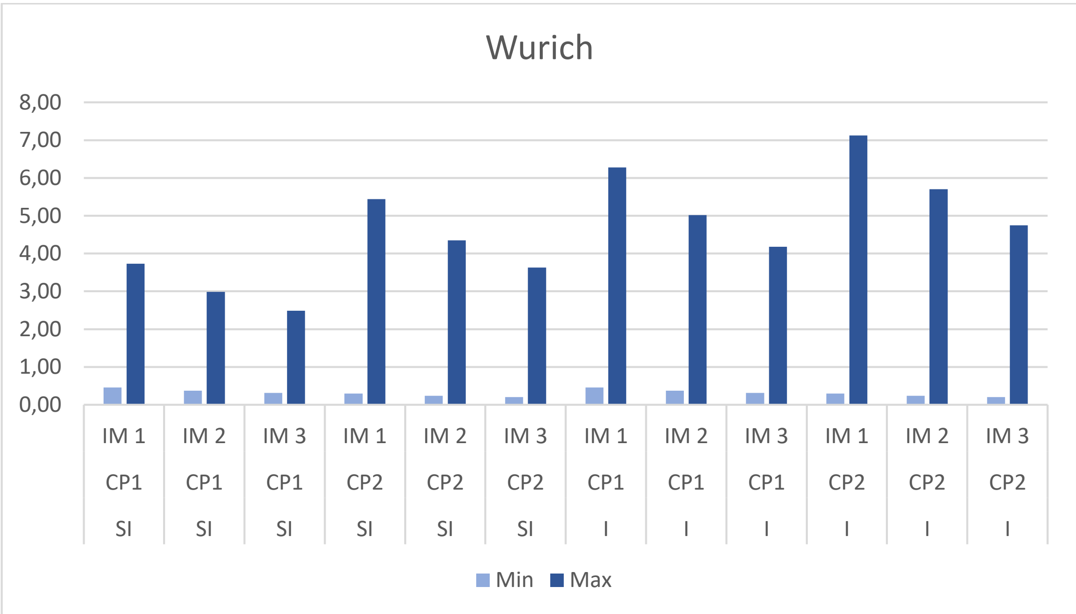

Figure 34: Overall Irrigation Water Demand for the Wurich Zone

The average minimum and maximum oIWD of the Wurich zone are the lowest compared to the other zones with 0.31 BCM and 4.64 BCM respectively. For the average minimum oIWD, the Dega zone follows with 6.2 BCM, then the Kola zone with 7.0 BCM and finally the Weynadega zone with the highest average minimum oIWD of 37.91 BCM. For the average maximum oIWD, the Wurich zone is followed by the Kola zone with 67.0 BCM, then the Dega zone with 120.1 BCM and finally the Weynadega zone with the highest average oIWD of 160.7 BCM.

Overall Irrigation Water Demands for the Blue Nile basin

Since the data shown above only reflects the annual oIWD per agro-economic zone, the values for each zone with matching other combination (cropping pattern, irrigation method and type) were summarized to display the annual oIWD for the whole catchment area. These are shown in Figure 35.

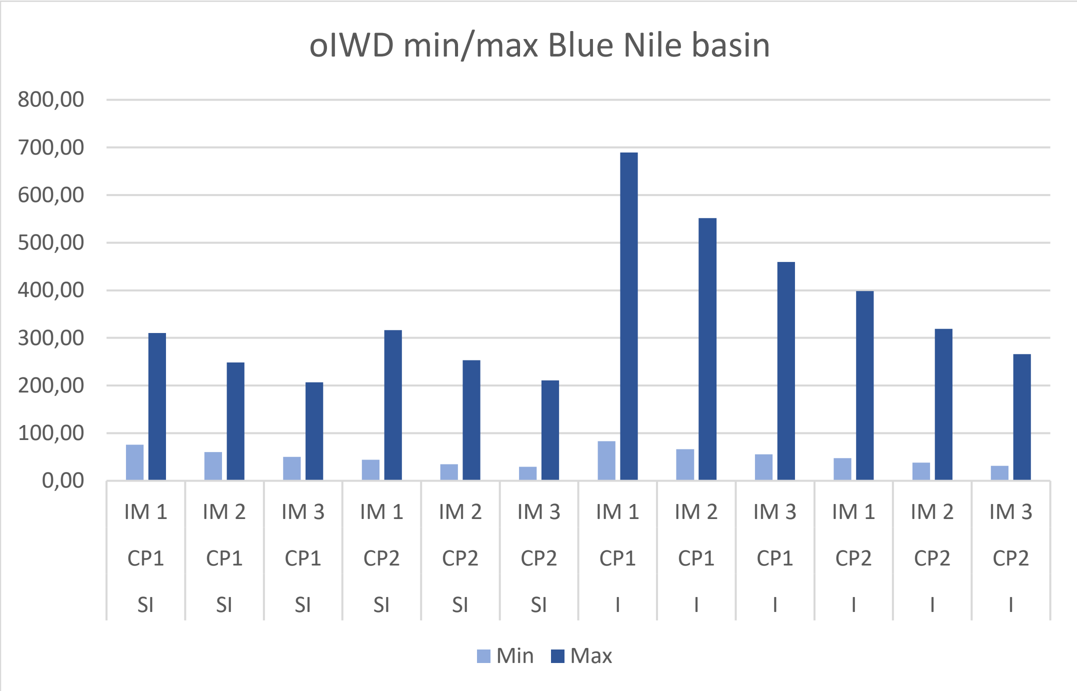

Figure 35: Combined annual oIWD in the Blue Nile basin for each application scenario

The minimal overall IWD was calculated for Scenario SI-CP2-IM3 with 29.25 BCM while the largest oIWD belongs to scenario I-CP1-IM1 with 689.28 BCM. Due to the nature of the irrigation methods getting more efficient, the decrease of the oIWD in these groups of three can be observed. Additionally, through the definition made to distinguish between the scenarios with supplemental and full irrigation, a clear difference in the equivalent scenario from these two irrigation types is visible. Some results, however, are unexpected. The two cropping patterns C1 for cash crops and C2 for food crops were initially developed to have different dimensions of water demand. Naturally, cash crops require significantly more water than food crops. This, however, did not become true when observing the maximal water demands for supplemental irrigation as displayed in Figure 35, as for example the two scenarios in each irrigation type with the same irrigation method SI-CP1-IM1 and SI-CP2-IM1, the food cropping scenario required about 6 BCM annually more than the cash crop scenario. As the other scenarios are only derivatives changing with the efficiency of the irrigation method, the other scenarios including supplemental irrigation show similar relations. For the full irrigation scenarios, the relations of the results are different. Here, a clear decrease from the water demands between cash crops consuming more water and the food crops doing less can be observed.

This research always had the overarching intent to identify the potential water abstraction from the Blue Nile River in Ethiopia. Compared to the annual discharge of the Blue Nile at GERD of 49 BCM, potential abstractions of up to 689 BCM as maximum or even 29 BCM at minimum seem very severe. The potential water abstraction for almost all scenarios except the ones for the minimal requirements of the food crops SI-CP2-IM1 (43.85 BCM), SI-CP2-IM2 (35.09 BCM), SI-CP2-IM3 (29.25 BCM), I-CP2-IM1 (47.54 BCM), I-CP2-IM2 (38.02 BCM), I-CP2-IM3 (31.70 BCM) are exceeding available water resource and hence are not realistic. As always, the results have to be understood carefully. As the study depicts a worst-case scenario in which every possible suitable area is cultivated, the results naturally are very high, while it must be doubted that this development will ever happen in this completeness. It also is questionable if the very tightly arranged cropping patterns as they were developed really can be implemented. The success of such patterns would also depend on optimal growing conditions so that the harvest can take place according to data provided in the available literature. Another factor hindering the complete development will be financial inputs. The partwise harsh terrain would need machinery to make the wild land arable in the first place, and also the cost for the irrigation infrastructure, which was not considered in this dissertation, might further limit the potential suitable area. As mentioned in section 2.3, inefficient methods like surface irrigation also requires low or no slopes as all which can only be found in few areas in the lowlands or on top of the plateaus. This would rather indicate the less water consuming methods to be more plausible. Additionally, as the goal of the Ethiopian government is to increase small-scale farming, a tight alignment of the farms without any unused spaces in between is questionable. The crops chosen for the cropping patterns have also been chosen intendedly to be very water-consuming, which does not necessarily reflect the typical crop choice of a small-scale farmer. Nonetheless, any increase of water use in the Blue Nile basin will have effects on the downstream countries Sudan and Egypt. Independent from that actual reduction of the river's discharge, the quality of the water will worsen as it is known from sewage water from agricultural areas, which are high in chemical remains from fertilizers and physical leftovers from the plants, which are often thrown in the sewage canals as well. This will reduce the possibilities and also the productivity of agriculture in the downstream countries.

Compared to other studies, the results are located in the range of previous results. This is not expected, especially because the results for the suitable area in section 6.2.4 exceeded most of the values from other researchers. The results, however, are not directly comparable. A study from Hiben et al (2022) for example estimated an irrigation water demand of 0.15 BCM for the Ghba subbasin in the Blue Nile area, which is 102,548 km^2 in size (Hiben et al. 2022). Extrapolated to the size of the whole Blue Nile basin, the water demand would be approx. 189.6 BCM which matches with the full irrigation scenarios of this word. There are other results available like from (Yimam et al. 2021) who only determined a water demand of 9 BCM, which is most likely due to their application of the Mike hydro Model and assuming higher efficiency for the irrigation methods. Additionally, the smaller set of crops was considered and the area initially identified as suitable was set to only 7,381.83 km^2, which is significantly lower than the 94.640 km^2 used in this dissertation.

7 Conclusion

This thesis served the purpose to elaborate on the three main questions related to future agricultural development on the Blue Nile Basin:

- **Which are the necessary datasets needed to evaluate certain areas for their agricultural suitability?**
- **How can a certain area be evaluated regarding its agricultural suitability?**
- **How large will the water abstraction from the Blue Nile River system be based on the developed scenarios?**

In this chapter, short summaries of all the previous ones are given and the research questions stated above will be answered in brief.

7.1 Summary

In the first chapter, the motivation to write this thesis was explained, the objectives to tackle were stated, and an outline of this thesis was given.

In the second chapter, comprehensive background information on the key aspects dealt with in this thesis was provided. These are a collection of available MCDA methods and how to apply them and the most commonly methods to obtain weights for the criteria used in MCDA, several approaches to assess land suitability for different purposes, as well as the basic information on water resources management, specifically in agriculture like irrigation methods, techniques and cropping systems.

The third chapter gives a more detailed introduction to the subject and the study area. The broader context, physical and climatic characteristics as well as the socio-economic and political status related to the planned construction of a dam cascade along the Blue Nile are explained. Lastly, existing agricultural projects with a focus on the two prominent ones at Koga and Finchaa were presented.

The fourth chapter comprised a selection of research and publications covering comparable topics. The review showed that only a few studies were done either with the same study area, the same goals, or the same criteria included. Many studies focus more on smaller partial watersheds of the Blue Nile or are limited to administrative districts, which simplifies gathering data from public sources, which do not lead to reliable results related to water abstraction in the Blue Nile watershed. Others do not cover the complete process from assessing land suitability, applying their own developed approach, over determining plausible cropping patterns to estimate the water demand for different scenarios of climate, cropping pattern, irrigation method, and type.

In the fifth chapter, the different steps of progress to reach the final workflow, specifically to estimate the suitable land for agriculture, is presented. Starting from quick and simple, therefore inaccurate and overestimating exclusion of areas, a more refined partially automated ArcGIS model was developed, but due to the prerequisite of being freely available, which is not the case for ArcGIS, this approach was dropped.

The sixth chapter consists of the explanation of the final workflow followed to estimate the share of land in the study area which can be used for rainfed and irrigated agriculture, and the types and forms of data necessary for this, and where to find them. The results for the suitable area were generated using the LSE software provided by the team around Thanh Tuan Nguyen from the Vietnamese National Museum of Nature. Afterwards, the design of the cropping patterns for each of the four eco-climatic zones occurring in the study area for both cash crops and food crops was described. Lastly, the irrigation water demand was estimated for scenarios with full and supplemental irrigation for the previously developed cropping pattern under consideration of surface, sprinkler and drip irrigation.

Objective 1: The availability of detailed, up-to-date, and area-wide data is one of the major challenges in remote-sensing when working in developing countries. Climate-related and topographic datasets mostly were available in good quality due to their origin from satellite measurements or through an international grid of climate stations on the ground. The climate data used for this research were precipitation and temperature. Basic infrastructural data like the location of cities and their population and the road network were easy to access through online sources as well. When it comes to on-site data like the physical and chemical soil properties such as the content of certain nutrients, pH, soil depth and texture, drainage properties, the share of coarse fragments or organic carbon, however, the data becomes less comprehensive. This is due to the necessity of detailed collection of data, which understandably might be of lower priority in developing countries, than it is in other parts of the world.

Objective 2: MCDA is the irreplaceable tool to determine whether a certain area is suitable for agriculture or not. The issue lies in the detail that numerous different methods are available, of which some are more tailored for different application fields, such as agriculture. Others have a stronger focus on economic decisions for companies. Almost all methods are relying on expert knowledge to some extent, which introduces a sort of bias when setting the weights for the criteria, which hardly can be removed. An approach to do so would be the involvement of a group of experts to determine the specific weights towards the decision problem. Just as in this research, it is recommendable to simplify the process so that people without expertise in MCDA could apply the workflow to their study area. Together with simplicity, always goes the inaccuracy of the results, which would need to be accepted in this trade-off.

Objective 3: 48 scenarios were developed to cover an adequate amount of combination of the most important factors: The Climate zone, the Irrigation scenario, the type of crops on which the cropping pattern was based on, and the irrigation method. For the climate zones, the four available zones Kola, Dega, Weynadega, and Wurich were considered. The two irrigation scenarios, full and supplemental, were included while full irrigation presumed the maximal irrigation until the plant gets harmed or no increase of the yield could be recorded, and supplemental is defined as the minimal supply of water so that the plant does not wilt. For the crop type, one cropping pattern each for regular food crops and economically more promising cash crops was developed. For the irrigation methods, the three most common ones – surface, sprinkler, and drip irrigation were considered. The results showed predictable tendencies. In general, less effective irrigation methods resulted in higher water abstraction values for the scenarios in which they were considered. Of course, the same applies of course for the full irrigation scenarios due to the set frame conditions. Surprisingly, it turned out that the cash crops did not consume more water than the food crops as expected. The results range from 29.25 BCM for supplemental irrigation for cash crop using drip irrigation assuming the lower limits of the plants' water demand to 689.28 BCM for full irrigation for food crops using surface irrigation assuming the upper limit of the plants' water demand.

7.2 Future Research

During the research, several potential for upcoming research to refine the results manifested. One of the main obstacles was lacking data, which was also brought forward by numerous other researchers working in the same area. To tackle this shortcoming, a more detailed on-the-ground preparation of data from local governments or NGOs would be necessary. It could, however, be possible that this kind of data exists but is not available for the public or online or both for unknown reasons. This leads, also for this thesis, to many assumptions which had to be made to progress. Examples would be crop selections, farmers' likability to change their practices to increase their revenue, or farmers' link to the markets. This in turn leads to somewhat forced generalized workflows yielding only limitedly reliable results. The key to achieving durable results is repetitively executed studies with changing variables to obtain outcome ranges in which the results might actually be.

Specifically related to this study, two shortcomings could be identified. The first is the determination of weights for the MCDA. As a result of the limitedly available complete datasets, the number of criteria was initially reduced. On top of this reduction, due to the nature of the applied LSE software where crucial criteria can be set as "limiting" factors but in turn loose their weight to the outcome since they are theoretically set to 100%, the remaining few factors were subsequently increased in their weights leading to questionable results which however could be confirmed in the validation process. To improve this situation, either the number of factors in general would have to be increased, which goes in conflict with the limitedly available data, or the weighting process needs to be changed to that limiting factors are not excluded from the weighting process anymore.

As mentioned on several occasions before, the observed study area turned out to be too large. This leads to many assumptions to be made, leading to generalized partially fuzzy results as described. A more detailed observation of smaller watersheds of the Blue Nile's tributaries, one for two dimensions smaller, would benefit the final outcome. Doing so would also open the possibility of actually measuring the calculated water abstraction at the river junctions to the Blue Nile. This approach, however, would again raise the known issue of lacking data for small-scale observation and in this detail would also require a larger research group for the public body in Ethiopia to complete this task. Since large water abstractions would harm Ethiopia's claim to use the dam cascade only for the generation of hydroelectric power, this option seems very unlikely.

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